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the use of architectural
ACOUSTICAL
materials

THEORY AND PRACTICE

ACOUSTICAL MATERIALS ASSOCIATION



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THE USE OF ARCHITECTURAL ACOUSTICAL MATERIALS

Theory and Practice

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The Acoustical Materials Association

The Acoustical Materials Association is an organization formed by manufacturers of architectural acoustical materials for the purpose of furnishing architects and others with reliable technical data on sound absorbing materials and their uses.

All manufacturers of such materials are invited to apply for membership in the Association.

In addition to the information contained in this publication, a separate bulletin entitled "Performance Data on Architectural Acoustical Materials" is available. It provides up-to-date technical data on products manufactured by Association members.

Information regarding the Association, its membership, publications and activities can be obtained from the members or their local representatives or by addressing Acoustical Materials Association, 335 East 45 St., New York, N. Y. 10017.

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1. Introduction

The use of acoustical materials to form the interior finished surfaces of rooms has become a familiar concept in present-day architecture. Although its primary function is to absorb sound, a modern acoustical material is designed to meet other practical requirements of room surfaces. Among these properties, which may vary in relative importance in different types of rooms, are appearance, light reflectance, resistance to flame spread and fire penetration, durability, and maintainability. When an acoustical material is used as an integral suspended ceiling with a common plenum over adjoining rooms, the possibility of sound transmission between rooms through the ceiling and plenum must be considered. Consequently, acoustical materials and structures are now available in many different forms suited to the particular architectural requirements of the various types of rooms in which they are used.

It is the purpose of this booklet, however, to discuss the basic function common to all acoustical materials, namely, the control of the acoustical properties of rooms by means of sound absorption. The sound which one hears in any room, whether it be an auditorium, a class room, an office, or a hospital corridor, consists of two parts: (1) the sound which travels directly to the ear from the point in the room where it originates, and (2) the sound which reaches the ear after being reflected one or more times from the room surfaces. When sound strikes the surface of any material, a part of its energy is absorbed and the remainder is reflected back into the room. Ordinary hard interior finish surfaces, such as plaster, concrete, and glass, absorb very little and reflect nearly all of the sound striking them. Acoustical materials, however, are designed to absorb a large proportion of the incident sound energy and reflect comparatively little. The function of an acoustical material in determining the acoustical properties of a room, therefore, is to control the *reflected* part of the sound which the ear receives.

The degree of acoustical control required in a given room depends essentially on the use of the room. In an auditorium, theater, church, classroom, or lecture hall, it is necessary to be able to understand speech clearly throughout the room or to listen to music under the most pleasing acoustical conditions. In such rooms, acoustical materials are incorporated with the room design in such a way that useful sound reflections are retained and harmful ones absorbed. On the other hand, the sound one hears in an office, a restaurant, a school or hospital corridor, a bowling alley, or a factory, can be classified almost entirely (except for conversation at close range) as undesir-

able *noise*. It is common experience that noise can be at least distracting and annoying, and may often interfere seriously with communication, comfort, and working efficiency. In such rooms, therefore, acoustical materials are used to remove as much reflected sound as is practical or feasible, thereby creating a more comfortable acoustical environment. This application of acoustical materials is referred to as *sound conditioning*.

There are, of course, certain types of rooms where good hearing conditions and noise control are equally important. These would include, for example, a school classroom for kindergarten or the lower grades, and a gymnasium or swimming pool where speech must be heard above the noise.

In the following sections, the engineering procedures which are used to calculate the effects of acoustical materials on room acoustics will be outlined, together with the criteria which govern the degree of control required for satisfactory results in various types of rooms.

II. Sound Reflection In Rooms

BASIC PROPERTIES OF SOUND

The action of sound waves in a room may be described by analyzing what happens in a typical auditorium seating, for example, 1000 persons. A vocalist is on the stage producing, at the moment, a single sustained tone. The vibration of his vocal cords generates *sound waves*, which travel through the air in the

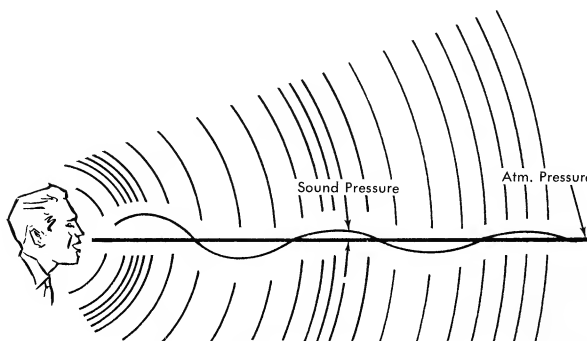


Figure 1. Generation of Sound Waves

form of very small changes in atmospheric pressure, alternately above and below the static pressure, as shown in Fig. 1. The average deviation in atmospheric pressure above or below the static value, due to

a sound wave, is called the *sound pressure*.^{A1} This sound pressure, by vibrating the ear drum, produces the sensation of hearing, and essentially determines the loudness of the sound as judged by the listener.

The sound waves travel outward in all directions from the vocalist's mouth in much the same manner that water waves spread outward on the surface of a pool from the point at which a stone is dropped. As the sound wave progresses, the sound pressure diminishes in proportion to the distance from the source, in the same manner that the water wave dies out as it spreads. Since sound pressure determines loudness, this effect explains the familiar experience of a sound outdoors becoming fainter as one moves away from the source.

In addition to pressure, sound waves have the important attribute of *frequency*. This is defined as the number of times per second that the sound pressure alternates above and below the ambient atmospheric pressure. Each complete alternation is called a cycle, and frequency is expressed in *cycles per second* (cps). The frequency of the vocalist's note is determined by the rate of vibration of his vocal cords, and the changes in frequency from one tone to another are perceived by the ear as corresponding changes in *pitch* of the musical notes. The higher the frequency, the higher is the pitch. The extreme range of frequencies which the ear can perceive is approximately 20 to 20,000 cps, although the upper limit decreases considerably with advancing age. The efficiency of acoustical materials varies with frequency, as do the loudness response of the ear and the performance of microphones and loudspeakers.

Sound waves travel through the air at a constant speed of 1125 feet per second (at room temperature), or a little over a mile in 5 seconds. The speed of sound travel is commonly observed as the time lag between lightning and thunder, or as the delay in hearing an echo from a distant cliff or wall. If our auditorium is 100 feet long, it will take about $\frac{1}{10}$ second for the sound to reach the back row from the stage.

DIRECT SOUND

Since sound travels in all directions from the source, the sound waves originating at the vocalist's mouth will strike the ears of every member of the audience. Each auditor will therefore hear that segment of the sound wave which travels in a direct line from the source to his ear. This is termed *direct* sound. Its loudness as heard by a given auditor will be determined only by how loudly the vocalist happens to be singing, or in other words by his *sound power output*,^{A2} and by the *distance* from the source to that auditor. For a given source power output, the loudness^{A3} of the direct sound increases by about one-half when the distance from the source is reduced by one-

half, as illustrated in Fig. 2. This shows that close to

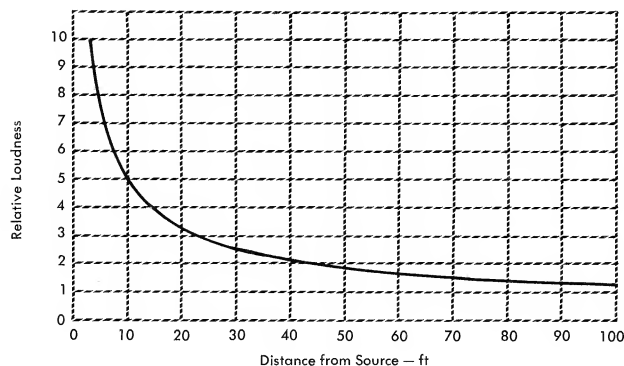


Figure 2. Relation of Loudness of Sound to Distance from Source, with No Reflection.

the source the loudness of the direct sound rises very rapidly as the distance is decreased, but farther away from the source a change in distance has relatively little effect. This partly explains the preference for front-row seats at a performance, and is further illustrated by the extreme change in loudness of sound picked up by a microphone or telephone transmitter when the speaker's mouth position changes by only a few inches.

REFLECTED SOUND

The sound originating on the stage travels not only to the ears of the audience but also to the interior surfaces of the auditorium. When a sound wave strikes a surface, its direction of travel is changed by *reflection* in the same manner as that of a ball bounced from a hard surface. This is shown in Fig. 3, illustrating the

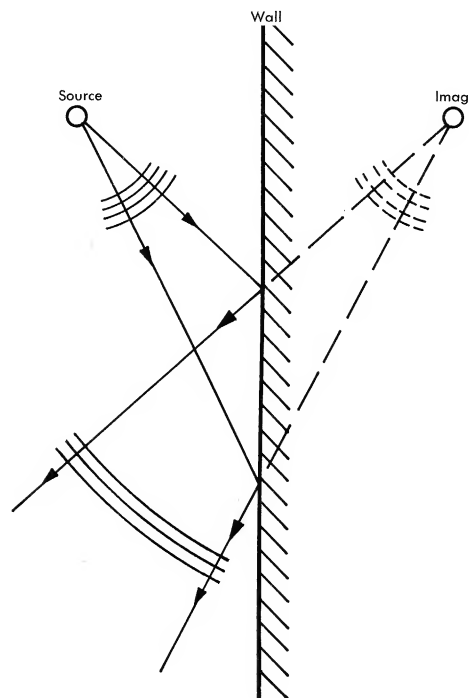


Figure 3. Reflection of Sound from a Plane Surface.

^{A1}More precise technical definitions and explanations of some of the terms used in the discussion are given in Appendix A, and are referred to by the superscripts, A1, A2, etc.

physical law that the angle of incidence equals the angle of reflection. If the reflecting surface is plane, the reflected wave will spread outward in its new direction of travel along exactly the same paths that would occur if the source had been behind the surface at the same perpendicular distance as the real source in front of it. This apparent source is called a *sound image*, in the same sense that an apparent source of light behind a mirror is termed a light image. The plotting of a sound image behind each plane surface is a useful short-cut in tracing the reflection of sound waves in the acoustic design of an auditorium.

In addition to the direct sound, an auditor will receive segments of the original sound wave which have been reflected at least once before reaching his ear. Several of the many possible reflected paths are illustrated in Fig. 4. The loudness of the sound arriv-

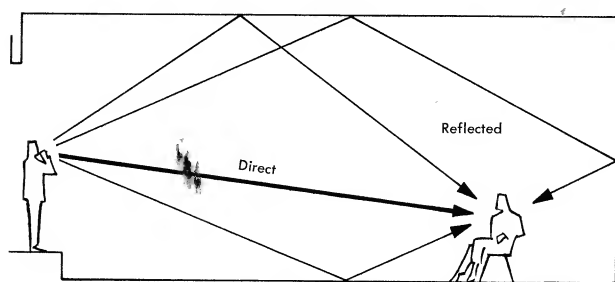


Figure 4. Direct and Reflected Sound in a Room.

ing at the auditor's ear by any reflected path will always be less than that of the direct sound for two reasons: (1) the reflected path is always longer than the direct path, resulting in a greater reduction in loudness due to distance; (2) all reflected sound loses some of its energy at each reflection. As long as the vocalist sustains his note, however, the auditor hears not only the direct sound, but the sound which reaches his ear by all possible reflection paths. The combination of all of the reflected components with the direct sound at the auditor's ear results in a total sound which is always *louder* than the direct sound alone. How much louder depends on the size of the room, the distance of the auditor from the stage, and on the absorbing properties of the room surfaces.

ABSORPTION OF SOUND

A sound wave in being reflected by a surface always loses part of its *energy*.^{A4} This loss of energy is termed *sound absorption*, and appears as a decrease in the sound pressure of the reflected wave with respect to that of the incident wave. The speed of travel, being constant for all sound waves, is of course not affected. The fraction of the energy of the incident sound which is absorbed during reflection is called the *sound absorption coefficient* of the reflecting surface. Hard, massive, non-porous interior finish surfaces, such as

plaster, masonry, glass, wood, concrete, etc., absorb generally less than 5 percent of the energy of incident sound waves and reflect 95 percent or more. Such materials therefore have absorption coefficients of less than 0.05. Porous materials which permit penetration of sound waves, or soft materials which yield under incident sound pressure, are capable of absorbing much larger amounts of sound energy, and may have coefficients approaching 1.00. Such materials include carpets, drapes, upholstered seats and furniture, the clothing of an audience, and acoustical materials.

ROOM ABSORPTION

As the various components of reflected sound reach the auditor's ear, as shown in Fig. 4, they will have lost energy in varying amounts depending on the total distance they have traveled between reflections, on the number of times they have been reflected, and on the absorption coefficients of the different surfaces encountered. However, these individual reflections, which may number in the hundreds, all combine in such a way that the total amount of reflected sound arriving at the ear from all directions and by all reflection paths combined is essentially the same regardless of the auditor's position in the room. The loudness of this reflected sound is determined first by the sound power output of the source. If the vocalist is singing loudly, the reflected sound at any auditor's ear (as well as the direct sound) will naturally be louder than if he is singing softly. The combined effects of absorption by the various room surfaces and the distance of sound travel between reflections on the loudness of the total reflected sound can be stated very simply in terms of a single quantity termed *room absorption*.

This quantity is obtained by multiplying the area in square feet of each room surface by its absorption coefficient, taking the sum of these products, and adding the absorption supplied by individual objects such as seats, furnishings, and persons. The absorption "*a*" of a given surface, or of an entire room, is given in units called *sabins*. One sabin is the equivalent of one square foot having an absorption coefficient of 1.00. Thus, for example, an area of 100 sq. ft. of a surface having an absorption coefficient of 0.80 would furnish an absorption of 80 sabins. The absorption of objects is usually stated as a certain number of sabins per object. An upholstered theater seat, for example, has an absorption of 3.0 sabins. In large rooms and at high frequencies, an appreciable amount of sound energy is absorbed by the air itself. The contribution of the air absorption should therefore be included in the total room absorption.^{A5}

For a given source power output, the *energy* of the total reflected sound at any point throughout the room varies inversely with the room absorption. It is determined *only* by the room absorption, and does not depend on the shape or size of the room, nor on the location or distribution of the absorbing surfaces,

except as these factors determine the total room absorption itself.¹ Thus, for example, if our vocalist performs in two auditoriums which are of similar shape and are finished with the same materials, but which differ in size, the loudness of his "fortissimo" note will be less in the larger room. This is because the larger room has the greater room absorption by virtue of its larger interior surface area. On the other hand, if the vocalist were rehearsing in an empty auditorium and then performing in the same room before a full audience, the loudness of the reflected sound would be less in the latter case because of the increase in room absorption due to the presence of the audience.

COMBINED DIRECT AND REFLECTED SOUND

For a sustained sound, the ear hears both the direct and reflected sound together, and the actual loudness of the combination will be governed largely by whether the direct or the reflected sound is the louder. As stated before, for a given source power output, the loudness of the direct sound depends only on distance from the source, and that of the reflected sound depends only on room absorption. These effects are illustrated in Fig. 5, which shows total loudness plotted

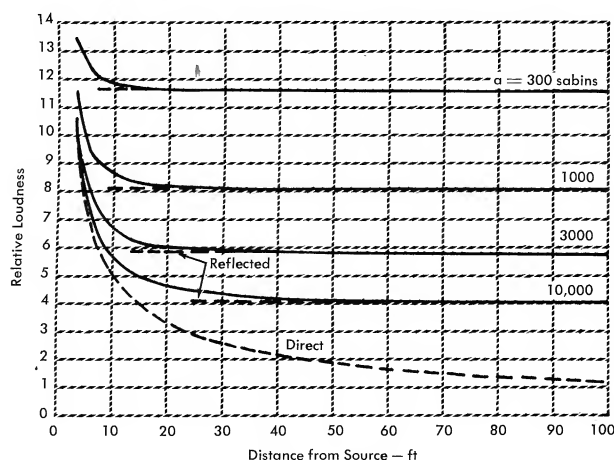


Figure 5. Relation of Loudness of Direct, Reflected, and Combined Sound to Distance from Source and to Room Absorption, a .

against distance from the source for various room absorptions. The curve for the direct sound is the same as plotted in Fig. 2. It is seen from these curves that close to the source, the total loudness is due almost entirely to direct sound and is therefore governed more by distance from the source than by room absorption. At points farther removed from the source, where the sound energy is mostly reflected, the loudness depends very little on distance and is determined almost entirely by room absorption. These

¹This statement is not strictly true under all conditions. For example, the sound energy at the rear of a low, deep under-balcony space may be appreciably less than in the open part of an auditorium. Focusing effects by large concave surfaces may also cause non-uniform sound distribution within a room.

effects of source distance and absorption are characteristics of rooms in general, and pertain equally well to noise sources, as will be discussed later in connection with sound conditioning.

REVERBERATION

We have discussed so far the loudness only of the vocalist's sustained note. When he cuts off his note, the direct sound heard by each listener will of course be cut off immediately. However, the sound waves which are already in the room will continue to travel back and forth between the room surfaces, and as these waves successively pass a listener's ear, he will hear them as a continuation of the sound after it was stopped at the source. The sound waves, however, lose energy by absorption at each successive reflection, and since this energy is no longer supplied by the source, the sound will be heard to die out more or less gradually. This prolongation and diminishing of the loudness of sound after the source has stopped, due to continued multiple reflection, is termed *reverberation*. If sound dies out very slowly, a room is described as "live" or "excessively reverberant", and if it dies out very rapidly, a room is called "dead".

Reverberation is one of the most important factors which govern hearing conditions in auditoriums, and it also has an important bearing on the "noisiness" of working areas. Of especial importance is its effect on the understanding of speech. If sound dies out very slowly in an auditorium used for speaking, the prolongation of each speech sound causes an overlapping and confusion of successive words or syllables which may render intelligibility extremely difficult or impossible. A similar effect is noted in music, where the sustaining effect of reverberation, if excessive, produces a blurring and lack of definition of melody and harmony. This is observed most strikingly when rapid organ music is played in a large, highly reverberant church or cathedral. In rooms where quiet surroundings are desired, reverberation is annoying because it prolongs distracting noises.

REVERBERATION TIME

The amount of reverberation in a room is measured by its *reverberation time*. This is defined as the number of seconds required for the energy of the reflected sound in the room to die out to *one millionth* of the value it had at the moment the source was cut off.^{A6} The reverberation time is a basic acoustical property of a room which depends only on its dimensions and the absorbing properties of its surfaces and contents. It is essentially the same throughout the room, regardless of the position of either the source or the listener. The reverberation time as just defined corresponds roughly to the number of seconds which a sound of "average" initial loudness can be heard by a person with normal hearing acuity before it dies out to inaudibility under completely quiet conditions. This may vary typically from a fraction of a second in a very dead room to the order of 5 to 15 seconds in a

very live room. For a given reverberation time, loud sounds can be heard for a longer period than initially faint sounds. The reverberation time itself, however, does not depend on the sound power output of the source.

The reverberation time of a room, like the reflected sound energy, varies inversely with the *room absorption*, as defined above. For example, doubling the room absorption will reduce both the reflected sound energy and the reverberation time by one-half. However, reverberation time also varies directly with the volume of the room, being in general longer in large rooms. This follows from the fact that in a large room sound on the average travels farther between room surfaces, and therefore reflections and the accompanying absorption occur less frequently.

EFFECTS OF ACOUSTICAL TREATMENT

From the foregoing discussion it will be seen that when the absorption of a given room is increased, as, for example, by introducing acoustical treatment, two effects will always occur: (1) the loudness of all reflected sound will be reduced (assuming the source power is unchanged), and (2) the reverberation time will be decreased. In the use of acoustical materials in auditorium design, the primary objective is to reduce reverberation only to the point where its harmful effects on hearing are eliminated. The amount of treatment required to accomplish this satisfactorily results generally in only a moderate decrease in loudness. Treatment much in excess of this amount would not only reduce the loudness unduly, but would also impart an unnatural and disagreeable "deadness" to the sounds produced in the room, particularly those of music.

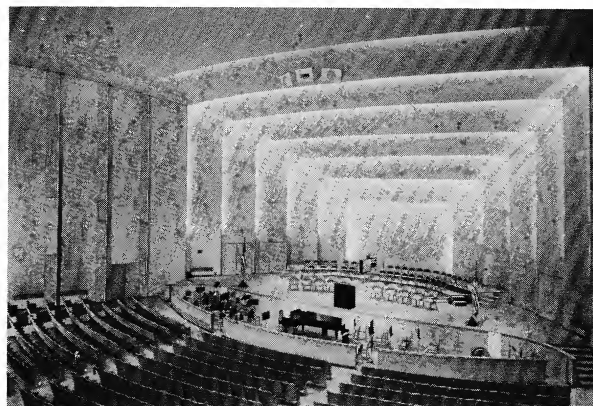
When acoustical materials are used for sound conditioning a work area, however, the principal requirement is to obtain as much loudness reduction as is practical or economically feasible, and for this reason considerably larger amounts of treatment are generally used than are required for correction of hearing con-

ditions alone. This loudness reduction is accompanied by almost complete elimination of reverberation.

An illustration of the relative effects of differing amounts of acoustical treatment applied in the same room is given in Fig. 6. This shows the building up of the loudness due to the accumulation of reflected sound (at a point far enough from the source that the direct sound is negligible) followed by the dying out of the reverberant sound after the source is stopped. The loudness reductions and the relative reverberation times shown are fairly typical of those obtained in practice when acoustical treatment is used for the two purposes indicated.

III. Acoustical Design Of Auditoriums

From the acoustical standpoint, an auditorium is any room intended for listening to speech or music. It may be a concert hall, a theater, a church, a high school auditorium or gymnasium, a court room, a class room, or a conference room. In all cases the primary



The acoustical design of auditoriums gives full consideration to the various types of activities that are to take place in the room.

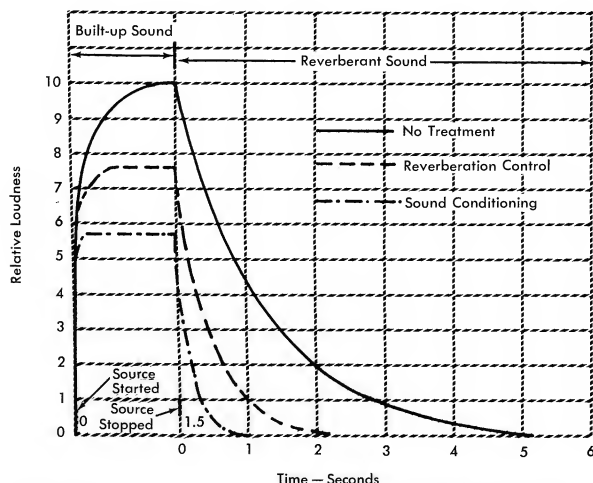


Figure 6. Chart Showing Building Up and Dying Out of Sound in a Room with Varying Absorption.

acoustical requirement is that speech be understood easily and without distraction throughout the room and that music, when presented, be heard under pleasing acoustical conditions. In general, there are four factors which must be considered in the acoustical design of a room in order to meet the above basic requirements as an auditorium, namely, (1) loudness, (2) noise, (3) first reflections, and (4) reverberation.

LOUDNESS

The first of these considerations, loudness, is important chiefly in the understanding of speech. It is common experience that a person cannot be understood if he does not speak loudly enough. As shown in the foregoing section, the loudness of a speaker's voice as heard at a listener's position not too close to the speaker will depend both on the speaker's sound power output and on the room absorption, and that the room absorption will generally increase with the size of the

room. A speaker will naturally try to raise his voice power in large rooms to compensate for the loss in loudness due to size and absorption, but his ability to do this is limited. It is necessary, therefore, and has virtually become standard practice, to provide speech amplification systems in large rooms. Because of the wide variation in the voice capability and experience of speakers, together with other factors such as background noise interference, it is impossible to set a fixed room size which determines whether speech amplification is necessary. However, amplification will generally be required in rooms of more than about 200,000 cubic feet volume, corresponding to a fairly large school auditorium or church. Amplification will also be more or less useful, depending on conditions, in rooms down to the size of a lecture room or small auditorium, namely, about 20,000 cubic feet. For smaller rooms amplification is usually not required, except possibly to overcome unusual noise conditions.

A speech amplification system should preferably be designed to reinforce the natural speaking voice without being readily apparent as a separate or artificial sound source. Loudspeakers, therefore, should be placed as near as convenient to the position of the actual speaker, and should be directed so that their projected sound covers the seating area uniformly. The amplification system, including microphones and loudspeakers, should have a uniform frequency response from about 500 cps up to at least 5,000 cps in order to provide maximum gain in intelligibility. Amplification of frequencies below about 500 cps is not necessary for speech intelligibility and serves only to enhance the naturalness of voice quality. A lower frequency limit of 100 cps is adequate for this purpose.²

In certain instances where it is impossible or unfeasible to lower the reverberation time of a room to a value representing optimum speech intelligibility, as for example in a large cathedral, amplification can be used to overcome to a limited degree the effects of excessive reverberation. This is done by the use of highly directional speakers which beam the sound directly to the seating areas. This results in a higher ratio of direct to reflected sound at each listener's ear than would be the case for a non-directional loudspeaker or for the unamplified voice, and is similar in effect to moving the listener closer to the source. The loudspeakers preferably are centrally located near the source, or under exceptionally difficult conditions may be a system of low-level units distributed around the room. In the latter case, each speaker covers a single section of the seating area, and is placed as close to that section as possible. In either case, the desired directionality of the loudspeakers is realized principally

in the higher frequencies, and for this reason it is especially important to project only the frequencies higher than about 500 cps.

NOISE

The second factor in the acoustic design of auditoriums, that of background noise, is closely related to loudness in its effect on speech intelligibility, and may be a source of serious distraction in listening to music. In the case of speech, the loudness of the speech must not only be above a certain minimum level for intelligibility, but it must also have a certain minimum ratio to the level of the noise in the room. Thus, for example, speech amplification might be necessary to overcome room noise, while it would not be required under quiet conditions.

Background noise may arise from many sources, such as outside street traffic, railways and aircraft, disturbance from adjoining rooms, ventilation noise, structure-borne vibration from mechanical equipment, and noise made by the audience itself. These sources may be controlled by various means, some of which depend on proper planning and site location of the building, and the use of adequate sound and vibration isolating construction. Acoustical materials are useful principally in the quieting of adjacent areas



Acoustical tile in this lobby muffles street noises and the buzz of conversation, preventing interference with listening in the auditorium.

such as foyers and lobbies, and, in the form of duct liners, for minimizing ventilating noise. The latter type of noise, due to its unobtrusive quality, is often underrated as a source of disturbance, and its interfering effect, especially with speech intelligibility, is realized only when it is eliminated.

FIRST REFLECTIONS

The control of first reflections, the third factor in auditorium design, is again important in connection with speech intelligibility, and also has an influence on musical quality. In the foregoing discussion of reflection and reverberation, no distinction was made between those parts of the sound which reached the ear after only one reflection, as against those arriving by multiple reflection paths. In the case of a sustained tone, as used in the example of the vocalist, the ear

² Amplification of music is seldom required in an indoor auditorium except for the reproduction of recorded music. For maximum fidelity of reproduction, a system having a flat frequency response from approximately 30 to 15,000 cps is usually recommended.

cannot distinguish these first reflections, and they are heard only as the beginning of the general reverberation. The syllables of speech, however, are of such short duration that the first reflections can be more readily sensed as distinct from either the direct sound or from later reflections. The relative prominence of these first reflections is due to the fact that they have lost less energy both by distance and by absorption than those parts of the sound which arrive at the ear after many reflections.

REINFORCING REFLECTIONS AND ROOM SHAPING

It has been found experimentally that reflections which arrive at the ear within an interval of 0.05 second later than the direct sound tend to reinforce the sound of individual speech syllables, while all later reflections have a blurring or interfering effect on the speech sounds which reduces clarity and intelligibility. The time interval of 0.05 second corresponds to a difference in path length between direct and reflected sound of about 50 feet. It is therefore possible, and is considered good practice in auditorium design, to arrange the room surfaces so that as much reflected sound as possible arrives at each seat by a path length not more than 50 feet longer than that of the direct sound, and also to suppress first reflections which arrive after path delays of more than 50 feet. This reinforcement by first reflections is particularly helpful in auditoriums where the loudness of speech without amplification is marginal, as for example in the use of a large theater for dramatic presentations.

For maximum effectiveness, the room surfaces which are utilized for reinforcement should provide reflected

paths which are as short as possible in relation to the direct path, and are as closely adjacent as possible to the direct path, so that the reflected sound arrives at the ear from nearly the same direction. This calls in general for ceilings not too high near the stage and for side walls which slope inward toward the stage, as shown in Fig. 7. It should be noted that this special shaping is effective only in moderately sized auditoriums, seating roughly 500 to 2000 people. In smaller rooms the first reflections are all naturally short enough in relation to the direct sound that special shaping for reinforcement is not necessary, and in much larger rooms it is difficult to provide short path differences to all parts of the seating area. In such rooms, even when well designed, it is frequently noted that hearing is indistinct in the front center portion of the main floor for this reason.

The effect of significant amounts of reinforcing reflection on musical performances is to impart a "close-up" or "intimate" quality to the sound, and to enable the ear to localize the direction of the source quite accurately. Delayed reflections, especially if they arrive from widely divergent directions give a more diffused, non-directional quality to the musical sound. These differences are audible quite apart from differences in overall reverberation time. In fact, it is possible to choose from a fairly wide variety of acoustical conditions in various seats of the same auditorium, depending on the varying pattern of first reflections, and it is sometimes found that the most distant seats have the most intimate acoustics.

ECHOES

If a first reflection of a short, impulsive sound such as a speech syllable is delayed more than about $\frac{1}{20}$ second after the direct sound, and if the room is relatively dead so that the reflection is not obscured by the general reverberation, the first reflection is clearly audible as a distinct repetition of the original sound. In this case it is called an *echo*. Echoes are heard only in fairly large rooms where reflecting surfaces are far enough away from both the source and the listener's position to permit the required path difference of 50 feet. Rear walls for this reason are the most common source of echoes.

When the sound source and the observer's ear are on the same perpendicular line between two parallel reflective room surfaces, the sound traveling back and forth along this line can sometime be heard as a *multiple echo*, or *flutter echo*. A further discussion of this effect is given on page 18. In auditoriums, when the source is at its normal position on the stage, multiple echoes are generally audible only when the wall behind the stage and the rear wall of the auditorium are both reflective.

FOCUSING

Serious acoustical difficulties due to echoes occur in general only when they are produced by *concave* re-

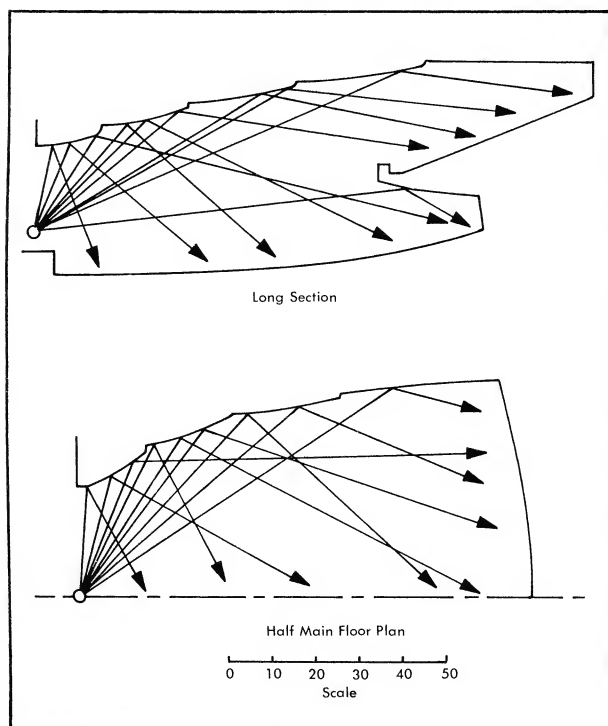


Figure 7. Auditorium Designed for Maximum Reinforcement of Direct Sound by Reflected Sound.

flecting surfaces, in which case they are termed *focused* echoes. As shown in Fig. 8, a focused echo is louder than one produced by a flat surface, because the sound rays converge after reflection from a concave surface.

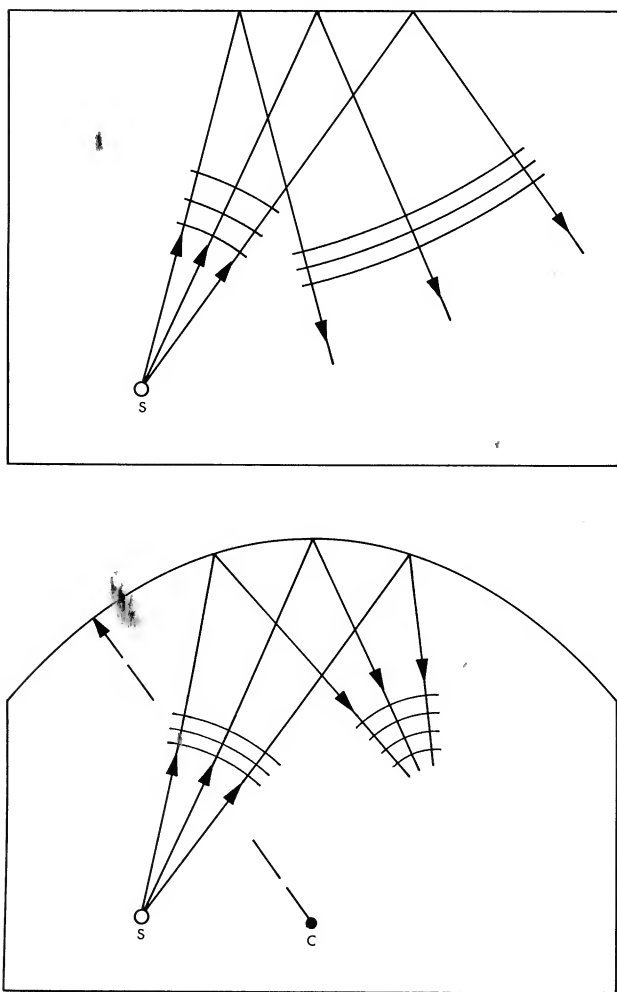


Figure 8. Regular Sound Reflection from a Plane Surface (Above), and Focused Reflection from a Concave Surface (Below). Source is at S, and Center of Curvature at C.

This convergence of sound rays results in a concentration of sound energy with resulting increased loudness. The most severe disturbance occurs when the sound rays converge to a small focal point close to a listener's ear. The effect is an abnormally strong echo which may actually be louder than the original sound, and which may come from a direction quite different from that of the original source. Strong focused echoes are always a distraction and if sufficiently delayed may render hearing of speech and even of music extremely difficult.

Curved rear walls are the most common source of focused echoes, although their curvature is usually small enough that the focusing effect is not severe. Reflections from curved rear walls should always be suppressed by treatment with highly efficient acoustical material, by tilting the wall downward so that sound is not reflected toward the front of the room, or by breaking the wall into splayed segments of a few feet

in width so as to scatter the reflected sound instead of focusing it.

Much more serious difficulties due to focusing are caused by circular or semi-circular floor plans, or by arched or domed ceilings where the center of curvature lies near the seating area. Acoustical treatment alone should *not* be depended upon to suppress focused echoes in this type of design. Instead, the building should be redesigned, if possible, so that centers of curvature are far removed from any of the seating areas, or the curved surfaces should be broken up by large irregularities of several feet in width. The use of suspended and separated flat panels below the main arch of a curved ceiling has been successful for this purpose.

Difficulties due to focusing may occur even when the delay of the reflected sound is not long enough to produce an echo. In this case, the focusing causes an abnormal increase in loudness in some parts of the seating area, usually at the expense of other parts, and often produces the effect of the sound coming from an entirely different direction from that of its actual source.

PLACEMENT OF ACOUSTICAL TREATMENT

The use of acoustical materials required for the control of reverberation in an auditorium may be effectively coordinated with the above outlined principles of acoustic design by applying a simple rule:

Acoustical treatment should be placed, to the extent feasible, on surfaces which cause delayed reflections to any part of the seating area in preference to those which provide significantly useful reinforcing reflections.

Rear walls and the front portions of excessively high ceilings and widely spaced side walls would be generally suitable for heavy treatment by this criterion. Ceilings less than about 25 feet high and wall surfaces shaped to provide useful reinforcing reflections are preferably left untreated, or else treated lightly or in partial areas. The above rule is applicable only to fairly large rooms seating at least a few hundred people. In smaller rooms, such as class rooms and conference rooms, as mentioned before, the surfaces are all close enough to both source and listener that there is usually no practical need for giving special attention to first reflections, either by room shaping or by placement of acoustical treatment.

STAGES

Reflecting surfaces can be utilized to especial advantage in the design of the stage, particularly in the case of musical performances. Although it is common practice in school auditoriums to line the stage completely with heavy drapes, much better acoustical results can be obtained by the use of reflective sets, or simply by leaving the stage undraped. Reflective stage surfaces provide useful support for the musicians themselves which enables each performer to hear the rest of the band or orchestra more clearly in relation

to his own instrument, and also help to project the sound more efficiently toward the audience.

REVERBERATION

The last and usually the most important factor in the acoustical design of auditoriums is control of reverberation. As mentioned previously, the reverberation time of a room is the single acoustical property which has the most to do with the intelligibility of speech and the quality of hearing conditions for music. The reverberation time depends only on the cubic volume of the room and on its total absorption, and is given by the formula^{A7}

$$T = \frac{0.05 V}{a}$$

where T = reverberation time in seconds,
 V = volume of room in cubic feet, and
 a = room absorption in sabins.

Sufficient knowledge has been accumulated concerning the absorption of interior finish materials, room furnishings, and objects such as seats and the members of an audience, so that the reverberation time of a room can be calculated quite accurately in advance of construction. Furthermore, a large amount of experience has been developed from which a range of acceptable reverberation times for a room of a given size and function may be stated with considerable certainty.

EFFECT OF REVERBERATION TIME ON SPEECH AND MUSIC

Experimental studies on speech intelligibility have shown that for reverberation times longer than about 2 seconds, the understanding of speech becomes increasingly difficult or impossible. As the reverberation time is lowered below 2 seconds, intelligibility and clarity of hearing steadily improve. With a reverberation time of about 1 second, hearing conditions for speech approach the ideal, and further lowering of the reverberation time produces no substantial improvement. It is also found that a lowering of the reverberation time can to some degree compensate for other adverse conditions, such as inadequate loudness or interfering noise.

Since hearing conditions for music are more a matter of taste and tradition than of intelligibility, acceptable reverberation times cannot be specified as precisely as for speech. There is actually a wide range of reverberation times which are considered acceptable for music of a given type and for a music room of a given size. However, the average requirements for performed music may be placed roughly within the following ranges:

Chamber music	1 to 1½ seconds
Orchestral, choral, average church music	1½ to 2 seconds
Large organ, liturgical choir	2 seconds or higher

Exceptions to these ranges are of course frequently made, as in the case of a piano or instrumental solo

recital being performed in a large concert hall whose reverberation time may be designed primarily for symphony orchestra.

Rehearsal rooms, such as school band rooms, due to their comparatively small size and the need for critical listening by the conductor, have been found most satisfactory when the reverberation time is between about 0.8 and 1.0 second.

CHOICE OF ACCEPTABLE REVERBERATION TIME

The results of expert opinion and research on reverberation times suitable for all types of room are collected in the chart of Fig 9. The band of reverberation times shown for a room of a given volume is intended as a range of design goals which takes

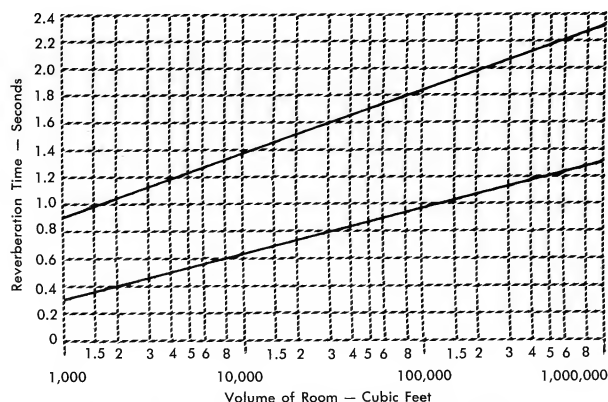
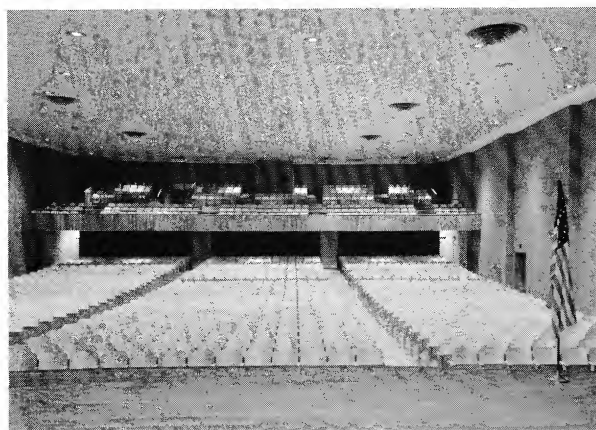


Figure 9. Range of Acceptable Reverberation Times, 500 cps.

account of the primary function of the room, and it is not implied that hearing conditions will necessarily be unsatisfactory for reverberation times outside of the indicated range. In the first place, it must be noted that the reverberation time of a room may vary at least over the range shown in the chart as the size of the audience varies. Secondly, as exemplified by a high school auditorium, a room may be used for a



Satisfactory hearing conditions in auditoriums and concert halls are dependent on size and shape as well as acoustical treatment.

wide variety of purposes ranging from speech in the empty room to a symphony concert or organ recital.

In using the chart for design purposes, the lower part of the band should be used for rooms intended primarily or exclusively for speech, and for rooms where all sound is reproduced, such as motion picture theaters. It should also be used for broadcast and recording studios, or any room used primarily for microphone pickup. The center of the band applies to general purpose rooms, such as high school auditoriums, civic theaters in which both speech and music may be presented, or the average church. The upper part of the band should be used for churches or concert halls in which organ and choral music are especially emphasized.

The next step is to select a value for the average size of audience expected in the room. This may typically be between one-third and two-thirds capacity. The acoustical design as far as reverberation control is concerned then consists of providing sufficient room absorption, either by furnishings or by acoustical treatment, that the selected value of reverberation time is obtained when the average size of audience is present. It is also advisable to calculate reverberation times for the empty room and for a capacity audience in order to estimate the variation in acoustical properties at these extreme conditions. A working rule for evaluating roughly the quality of hearing conditions in an average all-purpose auditorium or church over a wide range of reverberation times is as follows, assuming adequate speech amplification is provided:

Below 1 second	Good for speech, probably too dead for music
1 to 1.5 seconds	Good for speech, fair for music
1.5 to 2 seconds	Fair for speech, good for music
Over 2 seconds	Poor for speech, fair to poor for music

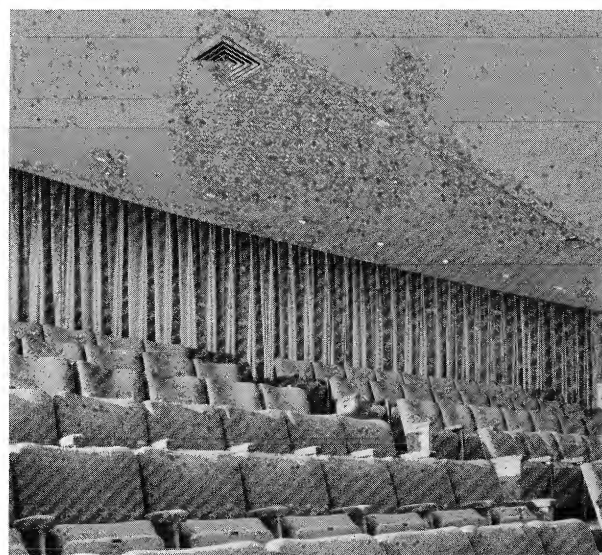
VARIATION OF REVERBERATION TIME WITH FREQUENCY

As noted previously, the absorption coefficients of all materials and objects vary with the frequency of the sound striking them, and therefore the reverberation time of a room will vary over the frequency range. The acceptable reverberation times shown in the chart of Fig. 9 pertain to the single frequency of 500 cps. This particular frequency is used mainly because most of the early data on acceptable reverberation times was obtained from measurements made only at this frequency. Calculations based on 500 cps alone usually serve as a fairly reliable index of hearing conditions over the entire frequency range insofar as they are related to reverberation time.

However, experience has indicated that extreme variations of reverberation time at other frequencies from the value at 500 cps will result in unsatisfactory hearing conditions. For example, a large excess of low frequency reverberation will produce a "boomy" condition, and a large deficiency at high frequencies may cause a muffled or "dead" quality. Various recommended curves of reverberation time vs. fre-

quency have been proposed.³ These generally specify a flat curve (no variation with frequency) above 500 cps. For music, a curve rising to about 1.5 times the 500 cps value at 125 cps is recommended, and for speech, a curve which remains flat down to 100 cps or lower is preferred. For a general-purpose room, the curve below 500 cps may lie anywhere between these limits. The exact shape of the reverberation-frequency curve is not critical, and deviations of ten percent from a selected curve at any frequency other than 500 cps may be considered allowable.

It may be pointed out in this connection that in cases where most of the room absorption is supplied by acoustical treatment, as for example a radio or recording studio, it is possible to approach a desired reverberation-frequency curve quite closely by choice of materials and mountings. However, in most auditoriums so much of the total room absorption is supplied by the audience, and possibly by upholstered



Frequently it is advisable to supplement acoustical ceilings with draperies to eliminate objectionable reflection from rear walls.

seats and absorptive furnishings, that the frequency characteristic of the acoustical material has relatively little effect on the final reverberation-frequency curve.

DETAILS OF REVERBERATION ANALYSIS

In order to illustrate the procedures used for obtaining acceptable reverberation times by means of acoustical treatment, the steps in the analysis of a typical school auditorium will be described in some detail. We will assume that the following data are available from the plans and specifications:

Average dimensions

Width — 60 ft. Length — 100 ft. Height — 30 ft.

Volume	180,000 cu. ft.
Floor surfaces	Concrete

³Leo L. Beranek, *Acoustics*, McGraw-Hill Book Company, New York, 1954, p. 426, Fig. 13.26.

Wall and ceiling surfaces	Plaster
Seating capacity	900
Seats	Leatherette upholstered
Stage	Fully equipped stage house with heavy stage curtain

The first step is to compute the volume of the room. In arriving at the above figure of 180,000 cu. ft., it is considered that the stage is in effect acoustically separated from the main auditorium by the stage opening and its volume is therefore not included. If the stage, however, were designed so as to form an extension of the auditorium proper, as for example in a concert hall or a lecture room, then its volume should properly be included in the total room volume.

The next step is to compute the total absorption of the room with no audience. This is done by multiplying the area of each component room surface in square feet by its absorption coefficient, and adding the absorption furnished by the seats. The coefficients for common building materials and various types of seats are listed in the table in Appendix B. Assuming that the analysis is carried out for the single frequency 500 cps, the computations yield the following values:

Floor, concrete	6,000 sq. ft. @ 0.015 =	90 sabins
Ceiling and walls, plaster	14,000 sq. ft. @ 0.03 =	420 sabins
Stage opening	800 sq. ft. @ 0.50 =	400 sabins
Seats, lightly upholstered with leatherette	900 @ 1.6 =	1440 sabins
Total room absorption, a		2350 sabins

It will be noted that the stage opening is assigned a coefficient of 0.50. In practice, the amount of sound reflected back into the auditorium from the stage opening will vary considerably depending on the amount of draping on the stage, on the size of the fly-loft, if any, and on whether the stage curtain is open or closed. The figure used is at best a rough estimate intended to represent average conditions in a school auditorium with a well-equipped stage. It will be noted also that the seats are assigned an absorption of 1.6 sabins *each*, instead of being computed on a square foot basis.

We are ready now to compute the reverberation times in the room with various sizes of audience, using the formula

$$T = \frac{0.05V}{a}$$

$$= \frac{0.05 \times 180,000}{a}$$

$$= \frac{9000}{a}$$

The value of a in the above formula will of course vary with the size of the audience and also with the amount of absorption which is added to the room in the form of acoustical treatment. We will carry out the calculations first for the room with no treatment, and for audiences of zero, one-third, two-thirds, and full capacity, respectively. It is to be noted that when a person is seated he covers up most of the absorbing surface of the chair, thus removing it acoustically from the room and replacing it with the absorption of his own clothing. The absorption of various types of seats has been measured both with and without an occupant, and for purposes of this example we will consider that the absorption of the occupied seat has a value of 4.0 sabins.⁴ The net absorption added to the room when each seat is occupied is therefore equal to 4.0 less the absorption of the empty seat. In our example, each member of the audience would add 4.0 less 1.6 or 2.4 sabins to the room absorption, and each one-third of capacity audience would add 300×2.4 or 720 sabins.

The reverberation times for the room with no treatment are computed as follows:

AUDIENCE	ABSORPTION a	REVERBERATION TIME $T = 9000/a$
0	2350 sabins	3.8 seconds
$\frac{1}{3}$	3070 sabins	2.9 seconds
$\frac{2}{3}$	3790 sabins	2.4 seconds
Full	4510 sabins	2.0 seconds

According to the rough criteria given in the table on page 12, hearing conditions for speech are not really satisfactory for audiences of any size, and for less than about two-thirds capacity are quite poor. The reverberation is excessive for music also with small audiences. Since a school auditorium is used quite frequently with small audiences, as for rehearsals or performances with limited attendance, lower reverberation times would appear desirable.

The next step in the analysis is to select an acceptable reverberation time as a design goal from the chart of Fig. 9. For a general-purpose auditorium of 180,000 cu. ft., the value indicated at the center of the band is about 1.5 seconds. Assuming that small

⁴In Appendix B, a range of values of the absorption of a seated audience is shown. The absorption per person will vary with the amount and type of exposed upholstery in the occupied chair, and will also vary with the amount of floor area taken up by each chair in the seating plan, not including aisles. It is found that the absorption of each person tends to increase as the floor area per chair increases. The higher values in the range shown should be used with large, heavily upholstered chairs and wide spacings between chairs and rows. The lower limit of the range applies to chairs at minimum spacing and with light or no upholstery. For further discussion, refer to Leo L. Beranek, *Music, Acoustics and Architecture*, John Wiley & Sons, Inc., New York, 1962, Appendix I, or Leo L. Beranek, *Journal of the Acoustical Society of America*, Vol. 32, p. 661, June, 1960.

audiences are fairly frequent, we will consider that this value of reverberation time should be obtained with a one-third audience. In order to determine the total absorption required to give the desired reverberation time of 1.5 seconds, we rearrange the reverberation formula to read

$$a = \frac{0.05V}{T}$$

Inserting the value of 1.5 for T , and 180,000 for V as before, we obtain

$$a = \frac{9000}{1.5} \\ = 6000 \text{ sabins}$$

From the tabulation above we see that with one-third audience the room already contains 3070 sabins; so that it will be necessary to supply the difference of 6000 less 3070, or 2930 sabins by means of acoustical treatment. If we assume that we can choose a material and an area of treatment such that exactly 2930 sabins will be introduced, we add this amount to each of the absorptions tabulated above for the various audience sizes and compute a new set of reverberation times for the room with treatment, as follows:

AUDIENCE	ABSORPTION a	REVERBERATION TIME $T = 9000/a$
0	2350 + 2930 = 5280 sabins	1.7 seconds
1/3	3070 + 2930 = 6000 sabins	1.5 seconds
2/3	3790 + 2930 = 6720 sabins	1.3 seconds
Full	4510 + 2930 = 7440 sabins	1.2 seconds

These reverberation times lie between 1 and 2 seconds for the entire range of audience sizes, and according to the criteria listed on page 12, the auditorium may be considered satisfactory for speech and music under all audience conditions.

EFFECT OF UPHOLSTERED SEATS

An important factor in auditorium acoustics is the absorption of the seats. To illustrate this effect, we will repeat the above computations on the assumption that the seats instead of being leatherette upholstered with an absorption of 1.6 sabins each, are of plain wood having an absorption of only 0.25 sabins each. In this case, the absorption of the empty untreated room will obviously be considerably lower, but the net added absorption of each member of the audience will be larger than with the upholstered seats. Using the approximate rule for computing audience absorption, the net absorption per person is 4.0 less 0.25, or 3.75 sabins for the wood seats, as against 2.4 sabins for the upholstered seats. Each one-third audience therefore adds 300×3.75 , or 1125 sabins, instead of 720. The reverberation times computed for the untreated room with wood seats are then as follows:

Untreated Room, Wood Seats

AUDIENCE	ABSORPTION	REVERBERATION TIME
0	1135 sabins	7.9 seconds
1/3	2260 sabins	4.0 seconds
2/3	3385 sabins	2.7 seconds
Full	4510 sabins	2.0 seconds

It is seen that for a full audience the reverberation time is the same as for the upholstered seats, but that for a small audience the reverberation time becomes much higher, and hearing conditions correspondingly much worse.

If the acoustical treatment is designed as before to give a reverberation time of 1.5 seconds with one-third audience, for which a total absorption of 6000 sabins is required, then the absorption to be supplied by treatment is now 6000 less 2260, or 3740 sabins, as against 2930 sabins with the upholstered seats. The reverberation times computed for 3740 sabins introduced by treatment are as follows:

Treated Room, Wood Seats

AUDIENCE	ABSORPTION	REVERBERATION TIME
0	4875 sabins	1.8 seconds
1/3	6000 sabins	1.5 seconds
2/3	7125 sabins	1.3 seconds
Full	8250 sabins	1.1 seconds

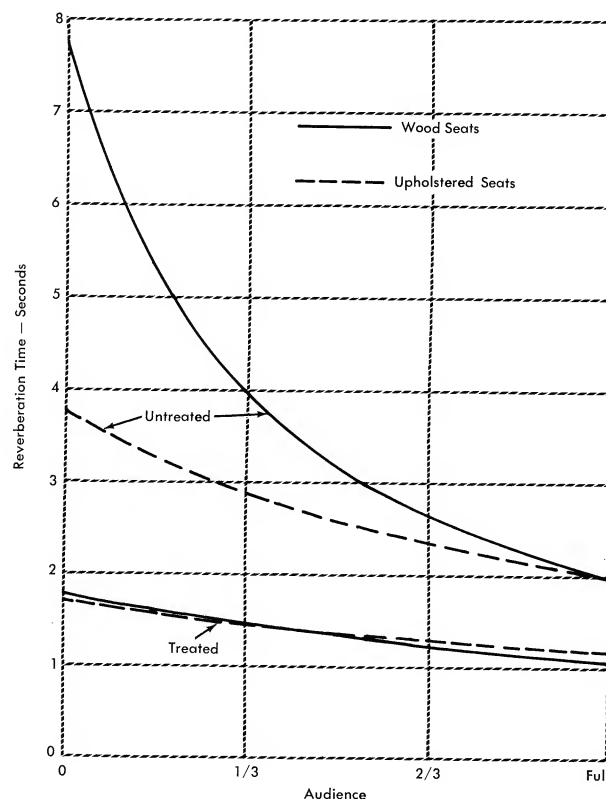


Figure 10. Variation of Reverberation Time with Size of Audience for Wood Seats and Upholstered Seats.

The reverberation times for all audiences still lie between the range of 1 to 2 seconds representing good hearing conditions, but there is somewhat more variation in acoustical conditions between the empty room and full audience. Upholstered seats are therefore of value acoustically in that they tend to equalize hearing conditions with respect to varying audience size, as shown in Fig. 10. It will be found that the larger the seating capacity in relation to the volume of the room, or, in effect, the lower the average ceiling height in relation to the floor area, the greater will be the effect of variations in audience size on acoustical conditions, and therefore the greater will be the equalizing effect of upholstered seats.

AREA AND PLACEMENT OF ACOUSTICAL TREATMENT

In following through the steps of the analysis of a typical school auditorium thus far, we have arrived at the number of sabins of absorption which is to be supplied by the acoustical treatment for each of two types of seating. In practice, the problem is now one of applying the required treatment in an acoustically and architecturally satisfactory pattern to available areas, in the case of an existing room, or of incorporating the treatment in the design of a new building. In approaching this problem it must be noted first that fairly wide tolerances in the computed results may be allowed without significantly affecting the final acoustical performance. A deviation of plus or minus 10 percent, for example, from the computed value of the required acoustical treatment is quite permissible. A tolerance of plus or minus 5 percent is allowable in computations of room areas and volumes and of estimating the coefficients of room surfaces. These tolerances afford considerable architectural design leeway in the selection of materials and areas for acoustical treatment.

The process of determining the area and coefficient of treatment required to furnish a given number of sabins is in practice somewhat cut-and-try. If, for example, a single material is chosen, having a given absorption coefficient at 500 cps, then the square footage required is given by the relation

$$\text{Area} = \frac{\text{No. of sabins required}}{\text{Coefficient}}$$

If, however, a certain area is available, one wants to know what coefficient a material should have in order to supply the required number of sabins in the given area. This is given by

$$\text{Coefficient required} = \frac{\text{No. of sabins required}}{\text{Available area}}$$

A material with approximately this coefficient, or possibly a combination of materials whose average coefficient approaches the desired value more closely, is chosen.

In further considering the particular auditorium example used in the foregoing, it would be recommended in view of the length of the room that all rear wall areas, above a wainscot level of 3 feet or so, be treated with a material having a 500 cps coefficient of at least 0.70. This would be especially important if the rear wall were curved. This would probably supply only part of the required absorption, and the remainder could be distributed on wall and ceiling areas in any pattern which is architecturally suitable. The rule given previously, however, should be observed if possible, namely, that treatment should not be placed on surfaces which provide a significant amount of reinforcing reflection to the seating area. In individual cases it is usually necessary to exercise some judgment in interpreting this rule in view of other practical requirements of room design.

IV. Sound Conditioning

As noted in the Introduction, an important use of acoustical materials is in the control of environmental noise in areas such as offices, banks, factories, restaurants, stores, school and hospital corridors, or in any room whose occupants may be exposed to annoyance and distraction due to noise. In fact, a much larger volume of acoustical materials is used for sound conditioning than for the correction of auditoriums. Thus, it has become virtually standard practice to provide



Lowered background noise results in easier speech communication—an important benefit achieved with acoustical ceilings.

continuous acoustical ceilings on all floors of a new office building or school, and at least in the corridors of new hospitals.

ANNOYANCE DUE TO REFLECTED NOISE

As also pointed out before, the essential function of acoustical treatment used for sound conditioning is to remove as much as possible or feasible of the *reflected* noise energy in a room. Experience has indicated that there are a number of subjective factors which may

contribute to the annoyance of reflected sound. These so far have not been evaluated in exact terms, but they can be roughly explained on the grounds that audible excessive reflection of a sound which is already disturbing is sensed as being unnecessary. The principal factors may be enumerated as follows:

(1) Multiple room reflection increases the loudness of all sounds generated in the room.

(2) With excessive reverberation, each sound is prolonged and the total noise exposure is correspondingly increased. This effect is most pronounced with discontinuous or impact noise sources, such as a typewriter, where the prolongation can be heard most easily, but is not present with continuous, steady sources such as rotating machinery.

(3) The normal decrease in loudness as one moves away from a source is lacking with high room reflection. Instead, the loudness becomes constant within a few feet of the source, as was shown in Fig. 5, and does not decrease as one moves farther away. This of course is desirable in an auditorium, but not in a room where the sound is unwanted. This tendency has been described as the "spreading effect" of noise in a highly reflective room.

(4) Since reflected sound arrives at the ear from many different directions, it becomes more difficult to determine the direction of the actual source as the amount of reflected sound increases.

The latter two factors combined tend to cause difficulty in locating sound sources by ear, as for example a ringing telephone. In some industrial operations, detection of the malfunctioning of machinery or of an emergency situation is done by ear, and sources must be located quickly and accurately.

EFFECT OF NOISE ON SPEECH COMMUNICATION

Probably the most sensitive and reliable criterion of the disturbance due to noise is its interference with speech communication. It is a familiar experience that as background noise increases, one needs either to raise his voice or to move closer to the ear of the listener in order to be understood. Improvement in speech communication, both at a distance and at close range, is one of the most frequently cited benefits of sound conditioning. It is especially helpful for close-range conversation or for telephoning because it lowers the level of only the background noise and not the speech level. It has been shown⁵ that if the loudness of continuous room noise is reduced by one-third, which is easily accomplished by sound conditioning treatment, a speaker at close range will need to use only about one-fourth as much voice power to be understood, or using the same voice power, he can move away to twice the distance from the listener's ear.

⁵C. M. Harris, *Handbook of Noise Control*, Ch. 9 by M. E. Hawley and K. D. Kryter, pp. 10-12, McGraw-Hill Book Co., Inc., New York 1957. The example given above refers to a reduction in speech interference level, defined as the sound pressure level averaged from 600 to 4800 cps, of 6 db. See also Appendix A, item A2.

The same figures would apply to the electrical power and speaking distances required for telephone or intercom systems.

The effect of sound conditioning on speech communication is of especial value in the case of discontinuous or impact noises. An excessively reverberant condition tends to sustain the noise peaks and create in effect a high, steady level of reflected sound. With reverberation removed, the noise peaks are both lowered and separated and it is often found possible to talk fairly well at close range between the peaks, even though the peak noise levels themselves may be considerably higher than the voice level.

EFFECTIVENESS OF SOUND CONDITIONING

From the foregoing discussion it can be seen that sound conditioning treatment is most effective in those situations where reflected sound, and its various effects, is the most pronounced and clearly audible without the treatment. The conditions for maximum effectiveness are in general (1) highly reflective room surfaces, (2) intermittent or discontinuous noise sources creating audible reverberation, and (3) listeners' positions which are not too close to one or more continuous sources. If the sources are of an intermittent or impact type, it is found from experience that sound conditioning is effective even though the listener is very close to a noise source. For example, a typist will find a sound-conditioned office more comfortable acoustically than a reverberant office because of the reduction of reflected noise, even though she is



The use of large-size sound-absorbing panels in an exposed grid system speeds the installation of acoustical ceilings.

too close to her own machine for its directly transmitted noise to be affected by the treatment.⁶ The same effect is observed in certain industrial areas, such as punch press rooms.

⁶T. F. W. Embleton, I. R. Dagg, and G. J. Thiessen, "Effect of Environment on Noise Criteria", *Noise Control*, Vol 5, No. 6, November, 1959. This study confirms previous indications that in a sound-conditioned office containing typewriters or business machines, the occupants will judge it to be quieter than a reverberant office even though the noise levels are the same, as measured at a worker's ear.

The limit of effectiveness of acoustical treatment is therefore the point at which all reflection is eliminated, and the ear hears only the sound which is transmitted directly from its source. This "free field" condition would be obtained by covering all room surfaces with a material having an absorption coefficient of 1.00 or 100 percent. It is very closely approached in specially treated test rooms called "anechoic chambers" or in the open air where the ground is the only nearby reflecting surface. The loudness of the remaining direct sound will then depend only on the sound power output of the source and its distance from the listener's ear. Further reduction in the directly transmitted noise can only be obtained by one or more of three means: (1) quieting the source itself, (2) placing a sound-retarding barrier between the source and the listener, and (3) increasing the distance between the source and the listener. As shown in Fig. 2, the last of these methods is much more effective at close range than at greater distances.

REQUIRED AMOUNTS OF TREATMENT

Because of the subjective nature of the result obtained by sound conditioning, it has not as yet been possible to establish criteria for the amounts of acoustical treatment required in various types of work areas which are as exact as those pertaining, for example, to speech intelligibility in an auditorium. Some working rules have been established on the basis of experience, however, which serve as a rough guide to these requirements.

Rule 1. In order for a room to be effectively sound conditioned, the average absorption coefficient of its surfaces should be at least 0.20. The average absorption coefficient is obtained by dividing the total room absorption a , including furnishings, by the total area of the room surfaces S , including floor, walls, and ceiling. While there is of course no sharp dividing line between acoustical conditions above and below an average coefficient of 0.20, it will be found that in most rooms the acoustical atmosphere becomes definitely "live" as the average coefficient is reduced much below this point. In general, therefore, sufficient absorption should be supplied by sound conditioning treatment to bring the average coefficient above about 0.20.

Rule 2. The practical upper limit for sound conditioning is an average coefficient of 0.50. As the average absorption coefficient of a room is increased by added amounts of acoustical treatment, the room becomes progressively more "dead", in that reflected sound is less apparent to the ear. With an average coefficient of 0.50, the audibility of reflected sound in relation to direct sound is negligible in most rooms, and any further reduction would require disproportionately large amounts of added absorption which might be structurally as well as economically impractical. For example, in order to obtain an average coefficient of 0.50, it would be necessary to cover the

entire ceiling and somewhat more than half the wall areas with a material having a coefficient of 0.90.

No set rules can be given for the exact amount of treatment required in a given room between the above working limits of 0.20 to 0.50. In general, however, the lower part of the range is suitable for large rooms with low ceilings containing noise sources widely spaced and not too intense. Such a room would be a large general office with a few typewriters. The upper part of the range is applicable to comparatively small rooms containing closely spaced or high-powered noise sources, such as a business machine room.

A third working rule applies specifically to existing rooms in which a noisy condition is to be corrected by sound conditioning treatment:

Rule 3. In order to create a satisfactory improvement in an existing room, the total room absorption (or the average coefficient) should be increased at least 3 times. The purpose of this rule is to insure that the change in acoustical conditions before and after sound conditioning is definite and unmistakable. However, its application should be governed by Rules 1 and 2. For example, if a room is very reflective, having an average coefficient of only 0.05, an increase of 3 times would bring it only to 0.15, which is below the acceptable limit for a sound-conditioned room as given by Rule 1, and an increase larger than 3 times would therefore be necessary. On the other hand, if a room such as a private office contains enough absorbent furnishings in the form of drapes, carpets, etc., that its average absorption coefficient is 0.20, an attempt to raise the coefficient 3 times to 0.60 would, even if possible, exceed the practical limit given in Rule 2. In this case, the room is marginally sound conditioned even before treatment, and the same change should not be expected as in a more typical work area.

LOCATION OF TREATMENT

The placement of acoustical treatment for sound conditioning purposes is dictated principally by the comparatively large amounts of absorption which are normally required. Since the ceiling is usually the largest and most readily available area for treatment, it is conventional practice to cover the ceiling entirely, and to place additional treatment, if required, on available wall areas. In large open areas with ceiling heights of 9 to 15 feet, such as a general office, an industrial plant, or a super-market, ceiling treatment alone with a material having a noise reduction coefficient⁷ of at least 0.60 is adequate to bring the overall average coefficient for all room surfaces well above the recommended lower limit of 0.20.

In other areas, the ceiling area may be a considerably smaller proportion of the total room area. This would occur in small rooms of average ceiling height,

⁷The noise reduction coefficient (NRC) of an acoustical material is defined as the average, to the nearest multiple of 0.05, of its absorption coefficients at the four frequencies 250, 500, 1000, and 2000 cps.

or in rooms with higher than normal ceilings, such as an open two-story bank. Also, available ceiling areas might be reduced by lighting or ornamentation. In such cases, additional treatment on wall areas may be



Sound-absorbing wall panels are often recommended as a supplement to acoustical ceilings in rooms having noise-generating business machines.

required. In small rooms containing one or more high-powered noise sources, such as business machine rooms or industrial test laboratories, extensive wall treatment in addition to ceiling areas is especially recommended.

FLUTTER ECHOES IN SMALL ROOMS

A phenomenon connected with the treatment of small rooms deserves special mention. If only the ceiling of a room of the size, for example, of a private office is treated and the walls are left perfectly bare and reflective, it is often observed that the room sounds much more live and reverberant than would be expected from the amount of absorption installed. This is due to the fact that sound waves traveling at angles which strike the ceiling are quickly absorbed, but those components which travel in horizontal directions continue to be reflected back and forth between the hard parallel walls with a much slower rate of absorption. When this horizontal multiple reflection occurs between a single pair of parallel walls, and is caused by a sharp impact sound, it is easily heard as a ringing or buzzing sound which is termed a *flutter echo*. It is most pronounced when the ear is on the same horizontal line as the sound source.

This condition sometimes causes dissatisfaction by the occupants of small offices, but can be easily corrected either by installing a strip of acoustical treatment at head level on one of each pair of parallel walls, or by placing diffusing objects such as pictures on the walls or venetian blinds on the windows. Such objects or surfaces are most effective when they are placed at a non-vertical angle of a few degrees so as to reflect sound toward the ceiling. Flutter echoes are also observed, but to a lesser degree, in larger



Sidewall acoustical treatment or the installation of vertical blinds will help prevent flutter echoes between parallel walls in small rooms.

rooms, notably gymnasiums where the ceiling is acoustically treated and the walls are left reflective and unbroken.

CORRIDORS

A very beneficial and widespread use of sound conditioning treatment is in corridors. Since the dimensions are so disproportionate, a corridor with reflective surfaces acts acoustically less like a room than a large speaking tube which conducts sound with very little loss of energy over its entire length. Hospital patients can attest to the degree of annoyance caused by this condition. Acoustical treatment results in a continuous drop in loudness along the length of the corridor away from the noise source, thus tending to confine disturbance to the immediate vicinity of the source.



Sidewall diffusion or wall acoustical treatment speeds up the absorption of reverberant sound in long hallways.

Noise reduction in corridors has not been thoroughly studied, but a convenient working rule may be stated as follows:

If the corridor width is greater than its height, ceiling treatment alone is adequate. If the width is

appreciably less than the height, treatment should also be brought down on the side walls so that the total width of treatment equals the ceiling height.

NOISE REDUCTION COMPUTATIONS

The criteria and procedures for sound conditioning have thus far been given mostly in qualitative terms. However, it is often desirable to make computations by which the effects of sound conditioning can be stated in more exact numerical terms. These computations may be made either in terms of sound energy, sound pressure level, or loudness. Of these various quantities, sound pressure level is the only one which can be measured easily by instrumental means such as a sound level meter, and for this reason is commonly used for engineering computations. *Sound pressure level (SPL)* is the term used to designate sound pressure when it is measured on the *decibel (db)* scale.^{A8}

It must be pointed out that the following computational procedures are entirely theoretical and are based on certain assumptions which may not always be justified in practical cases. The computations are found to be essentially correct under the following restrictions:

(1) The room is of fairly regular proportions, in that neither floor dimension is more than about 5 times the ceiling height.

(2) The average absorption coefficient (total absorption divided by total surface area of the room) is not more than about 0.30.

These qualifications are generally met in a room classified as an auditorium, but in sound conditioning applications may depart widely from actual conditions, as for example in a large general office with a heavily treated ceiling. In the following discussion it is assumed that the above restrictions are complied with.

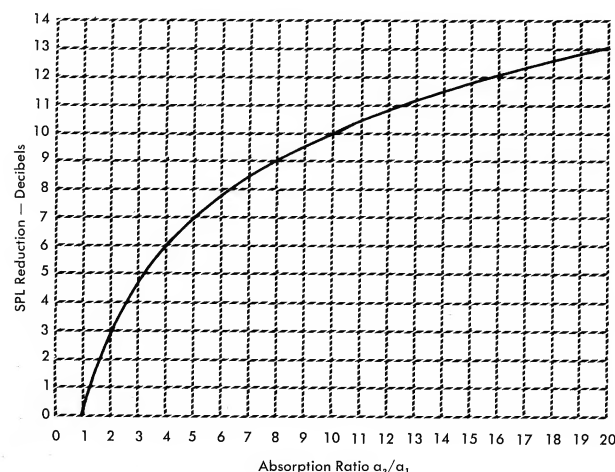


Figure 11. Relation of Decibel Reduction of Reflected Sound to Absorption Ratio.

We have seen from the general discussion of room acoustics in Section II that the energy of *reflected* sound is essentially uniform throughout a room, and

depends only on the sound power output of the source and on room absorption. For a given source power output, the reflected energy is inversely proportional to the room absorption a . If E_1 and E_2 represent the reflected sound energy in a room with a given source (or a number of fixed sources) before and after sound conditioning, respectively, and a_1 and a_2 are the corresponding total amounts of room absorption, then the inverse relation is given by

$$\frac{E_1}{E_2} = \frac{a_2}{a_1}$$

This means that if the total room absorption is increased 5 times by acoustical treatment, the *reflected* sound energy will be reduced 5 times, or to one-fifth of its previous value. It will be noted also that since the reverberation time is also inversely proportional to room absorption, the reverberation time will likewise be reduced to one-fifth of its former value. The quantity a_2/a_1 is termed the *absorption ratio*, and according to working Rule 3, given above, should generally be greater than 3 for a satisfactory improvement in a room.

Since for a given total room surface S , the average absorption coefficient $\bar{\alpha}$ is directly proportional to the room absorption a , the absorption ratio is also equal to $\bar{\alpha}_2/\bar{\alpha}_1$, and the above equation may be written in the alternate form

$$\frac{E_1}{E_2} = \frac{\bar{\alpha}_2}{\bar{\alpha}_1}$$

To express the reduction in reflected energy given by the absorption ratio in the above equations in terms of the difference in sound pressure level in decibels, the following is used, where SPL_1 and SPL_2 are the sound pressure levels before and after treatment, respectively:

$$\begin{aligned} SPL_1 - SPL_2 &= 10 \log \frac{E_1}{E_2} \\ &= 10 \log \frac{a_2}{a_1} \text{ decibels.} \end{aligned}$$

A plot of this equation is given in Fig. 11, from which the decibel reduction can be read directly from the absorption ratio. For the absorption ratio of 5 mentioned above, the reduction in SPL is read as 7 db. It will be noted that the *difference* in SPL in decibels is the same regardless of the original sound pressure level, and depends only on the absorption ratio. This is due to the fact that the decibel scale is itself a scale of *ratios* rather than differences in sound energy.

LOUDNESS REDUCTION

While a decibel difference in sound pressure level is an engineering quantity which lends itself to physical measurement, it is also important to know how the ear judges the change in sound energy due to sound conditioning. Apart from the subjective annoyance

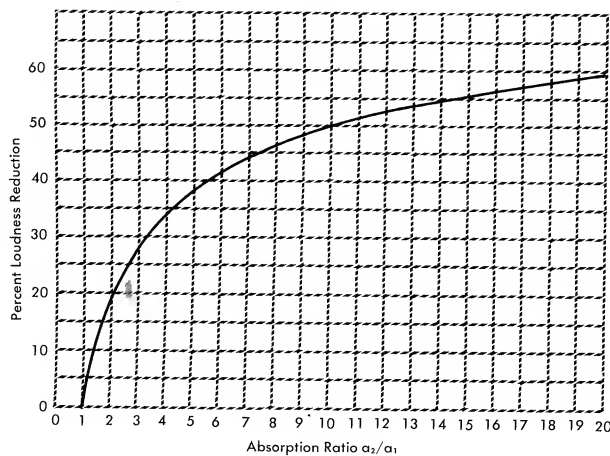


Figure 12. Relation of Percent Loudness Reduction of Reflected Sound to Absorption Ratio.

factors associated with excessive sound reflection as described previously, the ear is capable of making quite accurate judgments of the relative loudness of two sounds. An approximate relation between percentage loudness reduction of reflected sound and the absorption ratio is plotted in Fig. 12.

It is seen that, as in the case of the decibel reduction, the percentage loudness reduction does not depend on the original loudness but only on the absorption ratio. (The curve is drawn for loudness within the range normally encountered, and would not apply to extremely faint sounds.) Referring again to an absorption ratio of 5, the loudness reduction is read from Fig. 12 as approximately 40 percent. As a rule of thumb, it may be noted that in the range of reductions represented by most sound conditioning treatments, the percentage loudness reduction of reflected sound is about half of the percentage energy reduction. In the example given, the absorption ratio of 5 produces an energy reduction of 5 to 1, or 80 percent.

EFFECT OF SOURCE DISTANCE

All of the above computing procedures have pertained only to the *reflected* portion of the total noise in a room. As shown in Section II, the ear receives in addition the directly transmitted sound from each source in the room, and the loudness of each direct component is determined only by the sound power of each source and its distance from the ear. As shown in Fig. 5, the total loudness at a given listener's position with respect to a single continuous, steady source is determined principally by whether the reflected sound or the direct sound from that source is louder. At close range, the direct sound will tend to predominate, but on moving away from the source, a point will be reached where the reflected sound contributes most to the total loudness, and the loudness will tend to remain constant at further distances. The distance D at which this occurs increases with the room absorption a , and is given approximately by the relation

$$D = 0.5 \sqrt{a}.$$

These relationships, which were shown in terms of loudness in Fig. 5, are replotted as sound pressure levels in decibels in Fig. 13. The sound pressure levels shown on the vertical scale are arbitrary and are determined only by the sound power output assumed for the source. A source of different power would change only these levels by a fixed amount, and would not alter the remainder of the chart ^{A9}. The principal fact to be noted from these curves is that sound conditioning treatment is fully effective on the *total* loudness (or sound pressure level) of combined direct and reflected sound only at distances where the direct sound becomes negligible, and that this distance increases with room absorption. Since the absorption of an untreated room increases with size, this means that sound conditioning will be fully effective at closer distances to a noise source in a small room than in a large room. It is to be noted that the preceding statements apply only to the case of a steady, continuous source of noise, such as a piece of rotating machinery. If the source is intermittent or of an impact type, such as a typewriter, sound conditioning will be effective, as judged by the ear, at considerably closer distances to the source than indicated by the curves of Fig. 5 or Fig. 13.

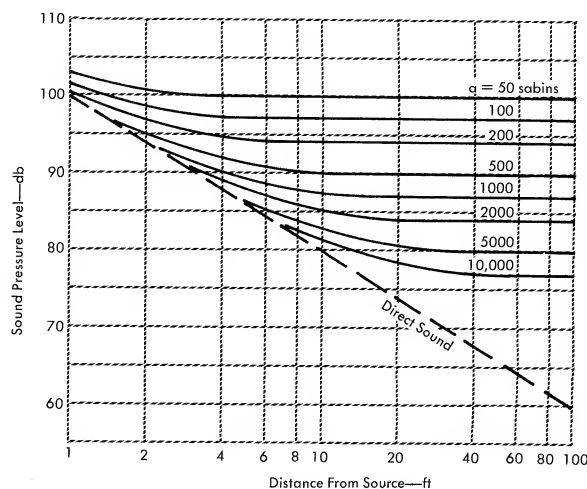


Figure 13. Relation of Sound Pressure Level of Direct Sound and of Combined Direct and Reflected Sound to Distance from Source and Room Absorption a .

COMPUTATIONS AT DIFFERENT FREQUENCIES

Because of the variation of absorption with frequency, the above computations are strictly valid only when carried out separately for individual frequencies, as is done when computing reverberation times for an auditorium. A computation of the reduction in SPL or loudness for a single frequency would then apply accurately only to that part of the overall noise in a room which contains frequencies at or near the one chosen. As an engineering approximation, however, computations are frequently made on the basis of the noise reduction coefficient of the acoustical material

and the other materials contributing to the room absorption. The mathematics involved in this approximation are such that noise reduction computations based on the NRC are more or less in error in predicting the actual reduction of noise containing the usual wide range of frequencies. This error will depend both on the frequency composition of the particular noise and on the absorption-frequency characteristic of the acoustical material being considered. For materials showing little variation of absorption with frequency the error is minimized.

EFFECT OF TREATMENT IN LARGE ROOMS

The foregoing computational procedures have been based on the assumption that the level of the reflected sound is uniform throughout the room, which is approximately true in rooms of fairly regular proportions. It is found, however, that in rooms such as a large general office or factory area where the floor dimensions are many times the ceiling height, the sound level does not become constant at a certain distance from the source, but tends to drop off continuously with increasing distance clear to the limits of the room. In very large rooms in which the ceiling is covered with highly absorptive treatment, the rate of decrease approaches that for the direct sound alone, namely 6 db. for each successive doubling of distance, or 20 db. for each 10-times increase in distance. This is the rate of decrease of sound level characteristic of free space. If the room is broken up by part-height partitions, large cabinets, shelving, etc., the rate of



Acoustical treatment of libraries and school study areas reduces distracting noise.

decrease may even exceed the free-space value. A similar continuous drop-off of sound level takes place in very large rooms even without acoustical treatment,

but at a slower rate. The effect of treatment in such a room, therefore, is to increase the rate of drop-off of sound level with distance from the source over the entire extent of the room.

Exact procedures are not available for computing this effect in terms of room dimensions and the coefficient of the ceiling treatment. It can be shown theoretically, however, that ceiling treatment is effective at closer distances to a source for low ceilings than for high ceilings. While the reduction in sound level due to treatment actually increases continuously with distance from the sources the reductions obtained within a range of distances from about 20 to 100 feet are roughly the same as the values which would be computed by the methods outlined previously on the assumption of a uniform level in the room.^{8,9}

V. Properties Of Acoustical Materials

In the introductory section it was stated that an architectural acoustical material combines the functions of sound absorption and interior finish. In this section, the characteristics of acoustical materials which govern both sound absorption and other properties such as appearance, durability, maintainability, and resistance to flame spread and fire penetration will be discussed.

The basic physical property of all practical acoustical materials which enables them to absorb sound is a structure of interconnecting pores. When a sound wave enters a porous material, the air within the pores is set into vibration, and the friction of the moving air against the walls of the pores transforms part of the sound energy into heat. The fraction of the incident sound energy thus transformed is said to be *absorbed*, and the remainder which is not transformed into heat is returned as a reflected sound wave of reduced energy.

All acoustical materials as normally installed in practice may be described in terms of three functional elements, each of which contributes to the sound absorbing efficiency of the installation. These are: (1) the layer of porous material, (2) the exposed outer surface or covering of the porous layer, and (3) the distance between the outer surface and the rigid structural backing, such as a plaster ceiling or concrete slab, to which the acoustical material is secured.

PORE STRUCTURE

The principal characteristic of the porous layer which governs its ability to absorb sound is its *air flow resistance*, which is a measure of the relative difficulty of blowing air through the material. If the flow

⁸C. M. Harris, *Handbook of Noise Control*, Ch. 18 by H. J. Sabine, McGraw-Hill Book Co., Inc., New York 1957.

⁹H. C. Hardy, "A Guide to Office Acoustics", *Architectural Record*, February 1957.

resistance is too high, because of too fine a pore structure or possibly a lack of complete inter-communication between pores, sound absorption will be low because sound waves cannot readily enter or penetrate the material. If the pore structure is too large and open, with a correspondingly low flow resistance, sound waves can easily enter, but the friction developed will be comparatively small and the absorption will again be low. In this case, the sound is reflected from the rigid backing and returns through the material back into the room with little energy loss. Materials having high sound absorption are designed with a pore structure approaching optimum flow resistance.

A porous material may take several physical forms, the most common of which is a felted mat of mineral or vegetable fibers. Materials formed of felted vegetable fibers are represented by the types listed in Tables 1 to 4, described as Cellulose Fiber Tile and Lay-In Panels in the classification of materials by appearance and composition in the annual Bulletin of the Acoustical Materials Association, "Performance Data on Architectural Acoustical Materials".¹⁰ Cellulose fiber tiles and boards normally depend for their strength and rigidity on the natural felted structure of the fibers, without the necessity for the addition of special binders. The flow resistance of a material of this type depends essentially on the density of the board and the fineness of the fibers.

Materials having porous elements composed of mineral fibers are included in Tables 5 to 14 in the above mentioned classification. These materials generally have either a felted fiber structure similar to the cellulose fiber materials or are composed of small granules or pellets of mineral fiber. In either case, the properties of mineral fiber in general, as contrasted with cellulose fiber, require the addition of a binder to provide suitable mechanical strength. For the materials having a pelleted structure, the flow resistance and sound absorption may also be affected by the amount and characteristics of the binder and by the pellet structure itself, as well as by the basic fiber properties.

Among less commonly encountered types of pore structure utilized in practical acoustical materials are those formed by small particles of solid material, such as pumice, vermiculite, or perlite, which are loosely bonded together so as to leave intercommunicating voids. Another type is a solidified foam which is processed in such a way that the bubbles are opened to form an intercommunicating structure. The latter type of structure may be either rigid or flexible, depending on the material used.

SURFACE

In order to meet the usual requirements of an interior finish, the exposed surface of an acoustical material

must have reasonable hardness, smoothness, durability, and light reflectance. In order to absorb sound, however, the surface must allow sound waves to penetrate freely to the porous element where absorption takes place. These requirements are met in various ways.

In general, sound-transparent surfaces are of three types. The first is a surface which is essentially hard and sound-reflective but which contains openings through which the sound waves pass. These openings may take various forms, such as the integral mechanical perforations or slots in the surface of a cellulose or mineral fiber tile or lay-in panel. The perforation patterns may be of a regular or random style, and may vary over a wide range of size and spacing. In every case, however, the surface of the tile or board is given a hard factory finish which is both sound and light reflective, and the perforations conduct sound through the surface to the underlying porous material. The percentage of open area in an otherwise impervious surface which is necessary for effective acoustical transparency varies considerably, depending both on the size and depth of the perforations and to some extent on the porous characteristics of the body of the material. A range of 2 to 15 percent open area is representative of most materials. The smaller the hole diameter, the smaller is the open area percentage required.

Another widely used means of penetrating into the body of an acoustical tile or panel is achieved by a fissuring process, exemplified by products in Tables 3, 4, and 6 of the AMA classification. These surface fissures are of a natural or simulated random pattern and are produced either in the manufacture of the basic board or by processing the exterior surface. In the case of tiles formed of pelleted mineral fiber, the surface contains in addition to the large fissures numerous smaller openings formed by the voids between the pellets. The size, number, and distribution of both types of openings have an effect on sound absorption.

A further variation of the reflective surface with openings is that in which the perforated surface is a separate element from the porous absorbing material, as described in Tables 10, 11, and 14. The outer surface is generally a pan or sheet of metal or asbestos board which may be perforated in a variety of patterns having the required percentage of open area. The absorptive element is a pad or blanket of mineral fiber which is laid in back of the facing, which in turn is attached to or mechanically suspended from the building structure. In this type of assembly, the porous element does not need to meet special requirements of strength or appearance, since these are provided separately by the facing.

An acoustical characteristic common to all of the above variations of a sound-reflective surface containing discrete openings is the fact that the transmission of sound waves through the surface varies with the sound frequency. At all frequencies up to about 1000 cps, a surface having perforation patterns typical of acoustical materials will transmit virtually all of

¹⁰Bulletin XXIV, 1964. As the Tables are subject to change, the order used in Bulletin XXIV is given in Appendix C.

the incident sound energy to the underlying porous material. Sound absorption, therefore, is appreciably affected by the pattern of surface openings only at frequencies of 2000 cps and higher, and will tend to drop off both with increasing frequency and with decreasing open area percentage. This effect is associated with the fact that at higher frequencies the sound wavelengths become comparable to the dimensions of the perforation pattern and the sound pressures incident on the reflective areas between perforations are less easily diverted into the openings. It is often noted that a variation in the perforation pattern may actually increase the absorption at frequencies of 1000 cps and lower. This is due usually to resonance effects involving the thickness of the material and the depth of the air space behind it.

The second general type of sound-transparent surface which is utilized in acoustical materials is a thin membrane of air-impervious material such as paper or a plastic film. Such a material, if free to move, is easily set into vibration by the pressure of incident sound waves, and its motion generates new sound waves on the opposite side. The incident sound is therefore, in effect, transmitted through the membrane. If the membrane is very light, it is easily vibrated, and virtually all of the incident sound energy is transmitted. Plastic films of sufficiently light weight are used as a surface covering for acoustical materials listed in Table 8. In one type of product in this category, the film is drawn over the surface of the porous tile or board, but is adhered only at the edges so that it is free to vibrate under incident sound pressure. In another type, the film is adhered continuously to the surface of the porous material, but in this case, the material is designed to have high enough resilience that the membrane can still vibrate freely. The absorption of membrane-faced materials varies with frequency in a manner similar to that of materials with perforated reflective facings. For membranes of the weights commonly used, absorption is not affected for frequencies below 2000 cps, but at higher frequencies it tends to drop off with increasing frequency and increasing weight of the membrane.

The third means of providing access for sound to the interior of an acoustical material is by leaving the exposed surface continuously porous. In this case, sound waves enter the material directly, instead of through distributed openings in a reflected surface. In this type of material, factory paint coatings on surface textures are applied in such a way as to provide suitable durability and light reflectance without impairing the surface porosity.

THICKNESS AND AIR SPACE

In order for sound to be absorbed by a porous material, it is necessary that the air be relatively free to move with respect to the porous structure. This freedom of movement is essentially zero immediately at the surface of the rigid structural backing to which the acoustical material is secured, and increases to a

maximum at a distance of about one-quarter wavelength out from the backing surface. It follows, then, that the effectiveness of a given layer of absorbing material increases as its spacing away from the rigid backing is increased up to one-quarter wavelength. It can also be seen that since the wavelength of a low-frequency sound is greater than that for a high frequency, it requires deeper spacings to obtain maximum absorption with a given material at low frequencies than is necessary for high frequencies. In general, the controlling dimension is the distance between the exposed outer face of the acoustical material, which may include a separate perforated facing, and the rigid backing. This space may be entirely filled with the porous layer, as when the material is secured directly to the structural backing. On the other hand, the material may occupy only a small fraction of the total space, as in the case of suspended ceilings.

In the first case, the face-to-back spacing is equal to the thickness of the material (plus that of an adhesive if used). Reference to the tables of absorption coefficients of current products shows that there is an average increase of about 0.10 in Noise Reduction Coefficient as the thickness of materials directly mounted to a solid backing (No. 1 Mounting) is increased from $\frac{1}{2}$ in. to $\frac{3}{4}$ in., with a similar increase as the thickness is raised to 1 in. This represents the practical range of thicknesses for most acoustical materials. Smaller thicknesses for materials against a rigid backing would result in inadequate absorption except at frequencies of 2000 cps or higher. Larger thicknesses would produce significant increases only at frequencies of 250 cps or lower.

When increased low-frequency absorption is desired, it is usually more feasible to use a material of $\frac{1}{2}$ in. to 1 in. thickness and provide an air space between it and the rigid backing, than to use large thicknesses of material in direct contact. Application of materials to a single course of wood furring (No. 2 Mounting) provides a nominal 1 in. air space and produces an average NRC increase of about 0.05, due principally to a substantial gain at 250 cps. Deeper air spaces of up to 12 or 16 inches produce correspondingly large increases in absorption at frequencies below 250 cps. These air spaces are provided by the No. 7 Mounting, which is designed to simulate the mechanical suspension of an acoustical ceiling below a structural surface.

The effect of deep air spaces on low-frequency absorption is most pronounced for those materials which are relatively porous through their entire thickness and thus allow sound to enter the air space after passing through the material. The thickness of the material when backed by a deep air space is in itself relatively unimportant except as it may affect the overall porosity or flow resistance of the porous layer.

MAINTENANCE

An important property of acoustical materials in most

applications is that of maintainability, that is, the procedure and technique required to restore the appearance and light reflectance of a material to a satisfactory condition after exposure to the normal soiling which is characteristic of the area in which it is installed. The maintenance procedure most commonly employed for interior surfaces in general is that of repainting. In the case of acoustical materials, the practical problem arises as to whether standard repainting procedures can be used, or whether certain modifications or precautions are necessary in order not to impair the sound absorbing efficiency of the material. While the recommendations of the acoustical material manufacturer should be followed explicitly in every case, some general comments can be made on this subject.

In the case of materials having mechanical surface perforations, which may be either integral or through a separate facing, virtually all of the sound energy which reaches the absorbent interior does so by way of the perforations. Any paint coating applied to the surface will therefore have a negligible effect on sound absorption provided the perforations are not covered over or reduced in size by the paint. The extent to which this may occur in routine painting procedure will, of course, depend on the original size of the perforations, and also on the amount of closure which may have been caused by previous paintings. For perforations of an original diameter of about $\frac{1}{8}$ " or more, the amount of closure and loss of sound absorption due to many repeated paintings is generally negligible. Since smaller perforations are more easily covered over, more care must be exercised in the painting procedure, and a fewer total number of repaintings can be performed without serious loss of sound absorption.

Actually, a considerable amount of closure can be tolerated under normal conditions of use. While no exact rule can be stated for all materials or occupancies, it is probable that in an average installation the total open area of perforations can be reduced by one-half, either by complete or partial closure, without reducing the acoustical performance to a definitely unsatisfactory level. It is quite possible, however, that a change of this amount would be readily noticeable by the room occupants, especially if it all occurred as the result of a single repainting.

The same considerations apply in general to materials with fissured surfaces. Since the fissures are sometimes relatively shallow, the precaution needed is to avoid filling in the fissures with paint. This technique is fairly easily carried out in practice, and materials of this type may therefore be considered paintable to about the same degree as those with the larger mechanical perforations.

Materials which depend entirely on surface porosity or on a very fine perforation pattern for sound absorption generally require special repainting techniques. For these materials, the paint coating must be applied in such a way as to avoid sealing the surface with a continuous, impervious paint film which would prevent

the free entrance of sound waves. This usually requires light spray applications of special non-bridging paints and a comparatively limited total number of repainting cycles. Materials for which these precautions are necessary include felted fiber tiles or panels without fissures or mechanical perforations of any kind, materials having very small or pin-hole perforations, and also, to a somewhat lesser extent, materials of pelleted mineral fiber composition which have not been fissured but which depend only on the small surface voids between the pellets for sound absorption.

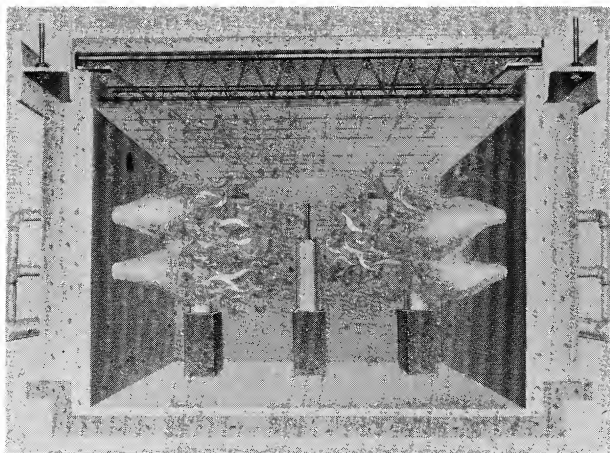
Although repainting is the more commonly used method for restoring appearance and light reflectance of acoustical materials, washing procedures are often employed. Most acoustical materials are provided with a factory-applied finish which is designed to withstand washing to varying degrees of severity and repetition, as recommended by the manufacturer. Perforated metal facings with an enamel paint finish provide high washability. Membrane faced materials are designed for maintenance primarily by washing, although painting can also be employed. Since an increase in the weight of a membrane facing will lower the absorption at high frequencies, as mentioned above, the weight of any added paint coating should be kept at a minimum. The manufacturer of a membrane-faced material should be consulted as to allowable paint weights, and also with regard to possible chemical incompatibility of the membrane with either paint solvents or washing compounds.

FLAME SPREAD AND FIRE RESISTANCE

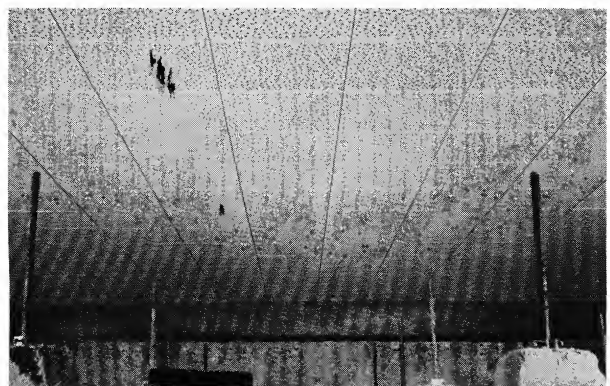
In discussing the fire resisting properties of acoustical materials it is important first to recognize that either or both of two different requirements may be under consideration in a given building or application. The first of these is termed *flame spread* or *flame resistance*, and pertains essentially to the degree to which the material will resist the spread of flame across its exposed finished surface under typical installation conditions. The theory is that the potential fuel, and the extent to which the ceiling might be the means of propagating fire from a point of origin can be specified and controlled. The degree of flame resistance of an acoustical material may be established by the nature of the basic materials, by the combinations of materials used, or by the employment of surface coatings especially formulated to resist the spread of flame.

The second type of requirement is termed *fire resistance*, and denotes the ability of a material to contribute to the overall resistance of an entire structure (typically a floor-ceiling structure) to the penetration of heat or fire from the side on which the acoustical material is installed to the other side. Tests for this property are normally made on the entire structure, including the acoustical material, and the results are stated as a time rating. In order to provide effective fire resistance, a material must necessarily be of noncombustible composition so that it remains in place, and must be attached to the main structure in

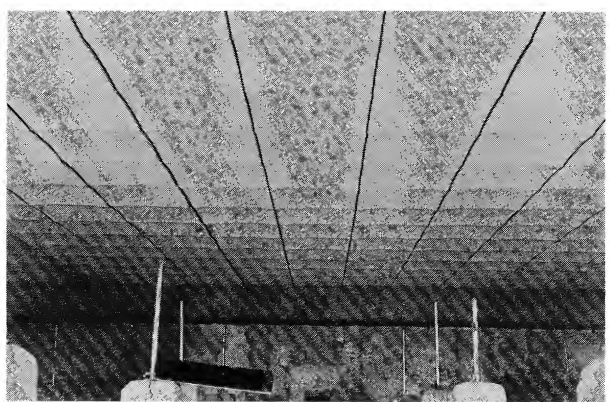
such a way that cracks are not opened to allow the penetration of flame or hot gas to the supporting structure.



Cross-section view of furnace showing bar joists supporting concrete floor and suspended acoustical ceiling. Pipes atop cylinders hold thermocouples.



View of a fire-resistant tile ceiling prior to exposure to furnace fire, in this case scheduled for 4 hours at temperatures up to 2000° F.



View of same ceiling after successfully passing test. Tile, although warped, remained in place and adequately protected steel and concrete above.

VI. Sound Transmission

In discussing the applications of acoustical materials thus far, we have been concerned primarily with

situations where the sources of sound or noise to be dealt with are in the same room as that in which the acoustical treatment is used. However, many familiar problems of room acoustics are encountered when sound or noise is transmitted from sources in adjoining rooms through walls, floors, and ceilings. Probably the most common complaint due to excessive sound transmission is the resulting lack of speech privacy, as between offices, conference rooms, class rooms, apartments, hotel and motel rooms, etc. Where speech intelligibility is not directly involved, transmission of unwanted sound, such as practice on musical instruments, loudspeakers, machine noise, etc., can still be a source of annoyance and distraction. It is important, therefore, to consider some of the basic aspects of sound transmission, and in particular to point out the relation of acoustical materials to this problem.

MECHANISM OF SOUND TRANSMISSION

It is evident that sound originating outside the room in which a listener is located can reach his ear only by way of one or more of the interior surfaces of the listener's room (termed for convenience the *receiving room*). These sound transmitting surfaces are therefore equivalent to secondary sound sources within the receiving room. Considered as sound transmitters, the surfaces are generally the usual solid walls, floor, or ceiling, but they may also be actual openings in the interior room boundaries, such as the crack around a door, a hole in a wall around pipes or utilities, or a connecting ventilating duct.

Solid, air-impervious room surfaces transmit sound by being set into flexural vibration. When this vibration is caused by the pressure of sound waves striking the other side of the wall due to a source in the adjoining room (termed the *source room*), the sound transmission is referred to as *airborne*. This is the type of transmission due to voices or loudspeakers. Vibration of the receiving room surfaces may also be set up by direct mechanical coupling of a source of vibration to some point in the building structure. This is termed *structure-borne transmission*. The most common examples are the impact of footsteps on a hard floor, and the transmission of vibration from a machine such as a motor or compressor which is in direct contact with the building structure. It is common experience in steel-and-concrete buildings that structure-borne sound can easily travel to rooms far removed from the source of vibration.

Openings between a source and receiving room of course transmit sound waves directly, without the intermediate mechanism of flexural vibration. Two rooms may also be separated by a material which is porous, rather than air-impervious, the most common example of which is an unpainted lightweight concrete block partition. In this case, sound waves are transmitted directly through the pore structure but with some loss of energy due to absorption in the pores. At the same time, incident sound pressure will

tend to vibrate the partition as a whole, resulting in some sound transmission by this means. The two modes of transmission are essentially parallel paths, and the overall transmission will be governed by which of the paths offers the least resistance. If the material is very open and porous, it will transmit sound with very little loss, regardless of its other properties. However, if the pore structure is very tight, or if an air-impervious coating is applied to one or both surfaces, the transmission will take place as a result of flexural vibration rather than direct passage through the pores, and will be determined essentially by the weight and rigidity of the material rather than by its porosity.

These considerations apply directly to acoustical materials when they are used as the suspended ceilings of two rooms having a connecting plenum. In this case, sound which reaches the receiving room from the source room by way of the common plenum is transmitted twice through the acoustical ceilings, and the plenum may be thought of as an intermediate or secondary source room. Transmission of this type will be discussed in further detail in later paragraphs.

COMPUTATION OF SOUND TRANSMISSION

Problems of sound transmission to which acoustical materials are applicable are generally limited to airborne transmission between two adjoining rooms. In this case, it is usually desired to know what sound pressure level (or loudness) will exist in the receiving room due to the presence of a sound or noise of a given sound pressure level in the source room. The difference in average sound pressure level between the two rooms is termed the *noise reduction* (also referred to as *sound reduction*)¹¹ and is stated in decibels. The noise reduction between any two rooms does not depend on the sound pressure level in the source room. For example, if the noise reduction is 30 db, the sound pressure level in the receiving room will always be 30 db lower than that in the source room, regardless of the source room sound pressure level. The noise reduction does, however, depend on several other factors, namely, (1) receiving room absorption, (2) number of separate paths, (3) transmission loss of each path, and (4) frequency.

RECEIVING ROOM ABSORPTION

As pointed out above, the various surfaces or openings which transmit sound into the receiving room may be considered as secondary sources having a total sound power output which is determined by the sound pressure level in the source room and by the transmitting properties of each surface or opening. For a given total power output from the transmitting surfaces, the sound pressure level in the receiving room, if observed at a point far enough from any one transmitting surface or opening that the sound level is

essentially that of the generally reflected sound, will depend only on the receiving room absorption. The greater the receiving room absorption, the lower will be the sound pressure level in the receiving room, and therefore the higher will be the noise reduction between the rooms. The effect of an increase in receiving room absorption on the noise reduction is computed in the same manner as for the case where a sound source is wholly contained in the room, and is given by the chart of Fig. 11.

SOURCE ROOM ABSORPTION

It might be supposed that the noise reduction between two rooms would depend on the absorption in the source room as well as that in the receiving room. It is true that for a given sound *source* of fixed power output in the source room, the sound pressure level in the source room will depend on the source room absorption in the manner shown in Fig. 11. Also, the higher the absorption in the source room, the lower will be the SPL in both the source and the receiving rooms. However, by noting that the noise reduction is defined as the *difference* between the sound pressure levels in the two rooms, it will be seen that the noise reduction is not affected by the source room absorption. As a general rule, when it is desired to reduce the sound pressure level in the receiving room to as low a value as possible for a given source in the source room, it is desirable to provide as much absorption as feasible in both the source and receiving rooms.

TRANSMISSION LOSS

In general, sound may be transmitted by several paths between rooms, but the simplest practical case is that in which the only path is a dividing partition having no openings or sound leaks. The essential property of such a partition which determines its sound transmission is its transmission coefficient, τ . This is defined, in a manner similar to the absorption coefficient, as the fraction of the energy of the sound incident on the source side of the partition which is transmitted by the receiving side. The transmission coefficient of an average partition is quite a small fraction, of the order of 0.0001 to 0.01, and it is therefore more convenient in computations to use an equivalent quantity termed the *transmission loss*, TL, stated in decibels. This is defined by the following relation

$$TL = 10 \log_{10} \frac{1}{\tau} \text{ decibels} \quad (1)$$

By this definition, a partition having a transmission coefficient of 0.001 would have a transmission loss of 30 db, and a transmission coefficient of 0.0001 would correspond to a 40 db transmission loss.

The transmission loss of a partition having no openings or sound leaks at joints or boundaries is essentially a basic property determined only by the materials and construction of the partition. The transmission loss

¹¹American Standard Acoustical Terminology, S 1.1—1960, American Standards Association, Inc., New York.

does, however, vary with frequency in a manner also depending on the construction of the partition. In general, the transmission loss tends to increase with frequency.

It can be seen that for a given sound pressure level on the source side, the total sound power transmitted by a partition of a given transmission loss is proportional to its area in the receiving room. The sound pressure level in the receiving room will therefore increase with increasing partition area and decrease with increasing receiving room absorption. These factors are expressed in the following equation for computing the noise reduction between two rooms:

$$\begin{aligned} \text{Noise Reduction} &= \text{SPL}_S - \text{SPL}_R \\ &= \text{TL} - 10 \log_{10} \frac{S}{a} \text{decibels} \end{aligned} \quad (2)$$

where SPL_S = average sound pressure level in source room, db

SPL_R = average sound pressure level in receiving room, db

TL = transmission loss of partition, db

S = area of partition on receiving room side, sq. ft.

a = absorption in receiving room, sabins

This formula applies strictly only to rooms in which the sound pressure level is substantially uniform throughout the room on both sides of the partition, excluding positions very close to the partition. As pointed out in Section IV, this condition is not obtained in rooms which have very large floor dimensions in relation to their ceiling height, especially if the ceiling is highly absorptive. For such rooms, the sound pressure level on either side would vary with the point of observation, and the noise reduction would therefore depend on the measuring positions in both rooms, in addition to the other factors included in the above equation. In practice, it would be observed that the sound pressure level in the receiving room would decrease as either the source in the source room or the point of observation in the receiving room was moved away from the partition.

In using the above formula for computations, it is assumed that the transmission loss of the partition is known from laboratory or field measurements as a function of frequency. Also, it will be noted that if the receiving room absorption happens to be equal to the partition area, the noise reduction will be numerically equal to the transmission loss of the partition. This condition is expressed by:

$$10 \log_{10} \frac{S}{a} = 10 \log_{10} 1 = 0$$

For a room with high absorption in relation to partition area, the noise reduction will be greater than the transmission loss, and vice versa.

The next simplest practical case is that in which the partition contains a door or window having a different transmission loss from the partition, but which is again assumed to have no sound leaks around its edges. For this case, the formula for computing noise reduction is as follows:

$$\text{Noise Reduction} = 10 \log_{10} \frac{a}{\tau_1 S_1 + \tau_2 S_2} \text{ db} \quad (3)$$

where τ_1 = transmission coefficient of partition

S_1 = area of partition (less door) sq. ft.

τ_2 = transmission coefficient of door

S_2 = area of door, sq. ft.

The transmission coefficients of the partition and door are computed from their corresponding transmission loss values (assumed known) by use of Eq. (1). It can be shown from Eq. (3) that, as would be expected, the noise reduction due to a combination of two surfaces of differing transmission loss is intermediate between that which would be obtained if the entire surface had either the higher or lower transmission loss. The same equation can be used for the special, but important, case where one of the surface areas is a direct opening between the rooms. In this case, the transmission coefficient of the opening may be taken as 1.0, corresponding to a transmission loss of zero db. By use of the formula given by Eq. (3), it can be shown, for example, that the presence of a direct opening occupying only 0.1 percent of the area of a partition having a transmission loss of 40 db could lower the noise reduction between rooms by more than 10 db. This illustrates the importance of thoroughly sealing all openings in or around a partition if the noise reduction provided by the basic partition structure is to be fully retained. Inspection of Eq. (3) will also show that the higher the transmission loss of the partition without leaks, the greater is the drop in noise reduction caused by an opening of a given size.

FREQUENCY

Since all of the quantities in the above equations except area may vary with frequency, computations of noise reduction are usually carried out over a range of frequencies of interest. The following frequencies are commonly used for sound transmission measurement and computations:

125, 175, 250, 350, 500, 700, 1000, 1400, 2000, 2800, 4000 cps.

In order to determine accurately the performance of a wall or floor construction in reducing transmitted noise, it is necessary to compare its curve of transmission loss vs. frequency with the curve showing the frequency distribution of the particular noise existing on the source side. For example, if the original noise is of predominantly high frequency, then the construction should have its highest transmission loss in the

same frequency region. It is desirable, however, to have a means for describing the performance of a construction, when exposed to an "average" noise, by a single number rating. In the past, it has been customary to use the numerical average of the transmission loss values at nine of the above eleven frequencies, excluding 1400 and 2800 cps. This rating, termed the *nine-frequency average transmission loss*, is often quite inaccurate in comparing constructions having widely differing TL-frequency characteristics. One single number rating method which has been recently proposed is the *sound transmission class* (STC).¹² This rating is based on the requirement that the value of transmission loss at any of the eleven measuring frequencies does not fall below a specified TL-frequency contour. The shape of this contour is drawn to represent the more common types of noise, and generally covers the requirements for speech privacy.

A more precise method of rating constructions specifically in terms of the intelligibility of speech transmitted from one room to another is the *privacy rating number*.^{13,14} This method takes into account the frequency characteristic of average speech and also of various types of background noise, such as street traffic or air conditioning, which may be present in the receiving room and which will tend to mask or obscure the sound of the transmitted speech.

TRANSMISSION BY SUSPENDED ACOUSTICAL CEILINGS

It has become a widespread practice in new building construction to use acoustical materials alone as an



Suspended ceilings provide a convenient method for modernizing old buildings as well as a means of concealing ductwork, etc. in new construction.

integral suspended ceiling, leaving a plenum space above for the accommodation of ducts, piping, etc.

¹²ASTM Designation: E90-61T, Tentative Recommended Practice for Laboratory Measurement of Airborne Sound Transmission Loss of Building Floors and Walls. Small tolerances below the contour are allowed at high and low frequencies.

¹³W. J. Cavanaugh, W. R. Farrell, P. W. Hirtle, and B. G. Watters, "Speech Privacy in Buildings", *Journal of the Acoustical Society of America*, Vol. 34, No. 4, April, 1962.

¹⁴"Speech Privacy Design Analyzer", published by Owens-Corning Fiberglas Corporation, 717 Fifth Avenue, New York 22, New York.



When room partitions extend only to the suspended ceiling or surmount it only a few inches, the ceiling plenum path of sound transmission may warrant investigation when analyzing the building for acoustical privacy.

The plenum usually extends over a number of rooms below. The dividing partitions may be carried only to the under surface of a continuous suspended acoustical ceiling, or they may extend just above the suspended ceiling, but not to the main structural ceiling above. In either case, as noted previously, the acoustical ceiling on either side of the partition together with the common plenum serves as a "flanking" sound transmission path which parallels the transmission directly through the dividing partition. If the acoustical ceiling is extremely light or porous, or if it is suspended in such a way as to allow numerous leakage paths around the ceiling units, the transmission by way of the plenum may be considerably greater than that through the partition. The result is an overall attenuation which may be much less than that which would be expected from the partition alone, and which may lead to an unsatisfactory situation.

An extensive study of this type of transmission has been conducted by the Acoustical Materials Association, and test values¹⁵ of the sound transmission of complete assemblies of acoustical materials used as suspended ceilings are listed in the current Bulletin of the Association together with sound absorption coefficients of the same materials. The test facility used for ceiling transmission measurements consists of a

¹⁵Tentative Method of Test, AMA-1-II, March 1, 1959, published by the Acoustical Materials Association.

pair of identical rooms having a common plenum formed by the suspended acoustical ceiling under test. The partition between the rooms has a high enough transmission loss in comparison with the ceiling that in most cases the sound transmission measured between the rooms is essentially that which takes place through the ceilings and plenum. The partition may be arranged either to contact the underside of the suspended ceiling or to extend just above the ceiling structure.

The test results are stated as the *Ceiling Attenuation Factor*, which is defined as the noise reduction in decibels due to transmission only by way of the ceiling-plenum path between the two rooms. The dimensions and absorptions of the test rooms are such that the Ceiling Attenuation Factor for a given ceiling material and construction is closely comparable numerically with the equivalent transmission loss of a partition dividing the two test rooms. For example, if the Ceiling Attenuation Factor for a given construction is 30 db (at a given frequency), this means that the noise reduction between the rooms due to ceiling-plenum transmission is 30 db, and also that in the absence of a plenum path the noise reduction due to a dividing partition having a transmission loss of 30 db would also be close to 30 db. This approximate equivalence holds only for rooms of the same general size of the test rooms, namely, about 10 ft. x 15 ft. x 10 ft. high. A more complete discussion of the test method and use of the results is given in the current Bulletin of the Association.

Experience in both laboratory and field testing of suspended acoustical ceilings has indicated the following:

(1) One of the weak points in the ceiling-plenum transmission path is the joint or seal between the dividing partition and the ceiling, especially if the ceiling is continuous over the top of the partition. Special closure panels are available with some materials and suspension systems for providing a better sound seal at this point. An insulation blanket laid over the top of the acoustical ceiling and extending out two or three feet on either side of the partition line is sometimes helpful.

(2) The performance of a suspended ceiling depends quite critically on how tightly the acoustical tiles or boards are fitted into the suspension system. Loose joints or cracks are especially harmful with materials which in themselves have relatively high sound attenuation.

(3) The overall sound attenuation of the combination of a suspended ceiling and a dividing partition is governed essentially by the weaker of the two. It is sometimes found that more sound is transmitted through cracks or openings in the partition, which otherwise has an adequate rating, than is transmitted through the ceiling-plenum path. This is most likely to occur with modular types of partition, where building irregularities can lead to sound leaks in the erected partition.

APPENDIX A

A1. SOUND PRESSURE

Sound pressure is the root-mean-square deviation of atmospheric pressure from its static value due to a sound wave. It is measured in dynes per square centimeter. A sound pressure of 1 dyne per sq. cm. is about that of conversational speech at close range, and is equal to approximately one millionth of atmospheric pressure.

A2. ACOUSTIC POWER

The acoustic power (sound power) of a source of sound is the rate at which it emits energy in the form of sound waves. Sound power is expressed in watts, and is in general a partial transformation of another type of power. For example, a loudspeaker of 5 percent efficiency will generate 0.05 watts of acoustic power when operating at 1 watt of electrical power input. A vocalist's power similarly depends on his lung power and the efficiency of his vocal cords.

A3. LOUDNESS

Loudness is a subjective quantity indicating the magnitude of the hearing sensation. Loudness is determined principally by sound pressure and to some extent by frequency. The relation of loudness to sound pressure has been established by extensive psychological testing and has been the subject of long efforts toward standardization. The relation used in this booklet is based on the curve proposed by Stevens.^{1,2} For frequencies above 500 cps and for ordinary loudnesses, this relation is given by

$$\text{Loudness} = K P^{0.6}$$

where K is a constant and P is the sound pressure. When the sound pressure is given as *sound pressure level* (SPL) in decibels (See Definition A8), the above equation results in a scale in which a 10-decibel increase in sound pressure level equals a doubling of loudness, as shown graphically in Fig. A-1. This scale is represented by the equation.

$$\log_{10} (L_1/L_2) = 0.03 (\text{SPL}_1 - \text{SPL}_2)$$

where L_1 and L_2 are the loudnesses corresponding respectively to two sound pressure levels SPL_1 and SPL_2 . The unit of loudness is the *sones*, one sone being the loudness of a 1000-cps tone having a sound pressure level of 40 db.

A4. SOUND ENERGY (Sound Energy Density)

Sound energy (density) may be defined in architectural acoustics as the amount of energy contained in a

¹S. S. Stevens, *Journal of the Acoustical Society of America*, Vol. 28, p. 807, 1956.

²For a general discussion of loudness, see C. M. Harris, *Handbook of Noise Control*, Ch. 5 by W. A. Munson, McGraw-Hill Book Co., Inc., New York, 1957.

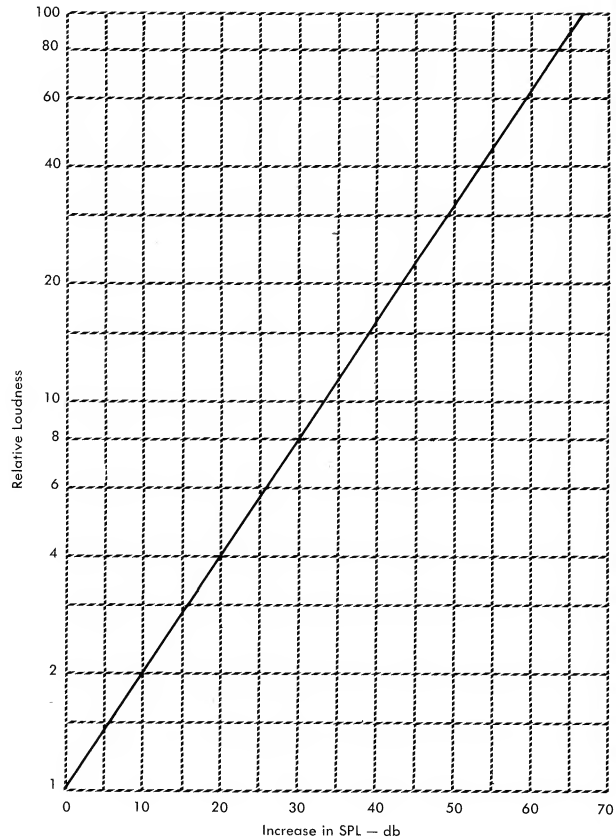


Figure A-1. Relation of Loudness Changes to Changes in Sound Pressure Level. Curve is Valid for Frequencies of 500 cps and Higher.

small unit volume of air at a given point in a room due to the presence of one or more sound waves passing through that point. The energy of each sound wave is proportional to the square of the sound pressure of that wave, and the total energy is the sum of the energies of the component waves. It is this additive property of sound energies which makes it a more useful quantity than sound pressure in describing the basic concepts of room acoustics.

A5. AIR ABSORPTION

A sound wave in passing through air loses a certain fraction m of its energy for each unit of distance traveled by absorption in the air itself. The total contribution of air absorption in a room is directly proportional to the volume of the room, V , and is given by

$$a_{(\text{air})} = 4mV \quad \text{sabins}$$

This is added to the absorption furnished by the room surfaces and contained objects to give the total room absorption. The attenuation coefficient m is very small for frequencies below 2000 cps, but increases rapidly at higher frequencies. It also increases greatly with decreasing relative humidity down to about 20

percent RH. Curves³ of air absorption, given in sabins per 1000 cubic feet of room volume, are plotted against relative humidity for various frequencies in Fig. A-2, for a temperature of 68°F.

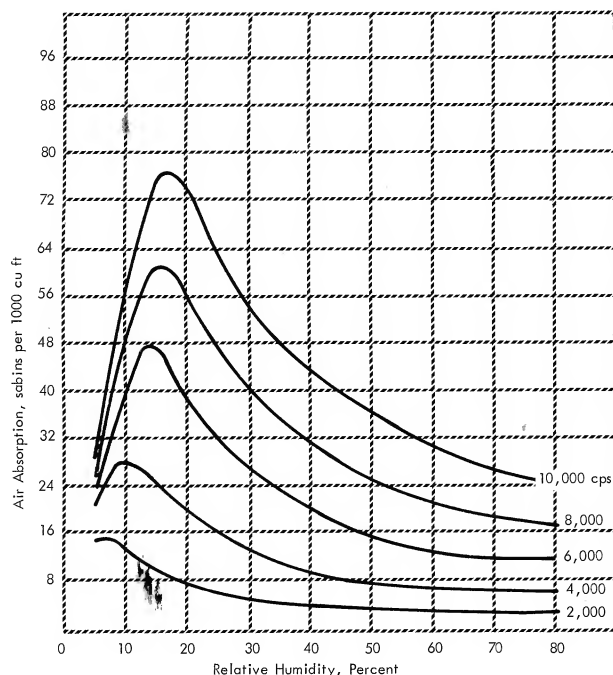


Figure A-2. Relation of Air Absorption to Relative Humidity and Frequency for a Temperature of 68°F. (After Harris.)

A6. REVERBERATION TIME

An equivalent definition of reverberation time is the number of seconds required for the *sound pressure level* of the reflected sound to die out to a point 60 decibels below its initial value (See Definition No. A8). This definition of reverberation time, and the formulas given on page 11 and in A7 below for computing it, are based on the assumption that the sound pressure level of the decaying sound when plotted against time is a straight line, neglecting minor fluctuations, over a range of at least 60 db. This is generally true in rooms having fairly regular proportions, shapes which are not exactly rectangular, fairly uniform distribution of absorbing material over the room surfaces, and moderate amounts of total absorption in relation to room size. These conditions are essentially met in most auditoriums. However, in perfectly rectangular rooms, having all of the absorption concentrated on the ceiling or on the floor and ceiling, leaving all walls reflective, as in a typical office, it is more usual for the sound pressure level to decay initially at a rapid rate, followed by a slower rate. This double decay rate is due to the fact that the sound waves which strike the ceiling are absorbed very quickly and the remaining sound waves which travel horizontally between the

reflecting walls are absorbed more slowly. Under these conditions, the above definition of reverberation time has no meaning, and neither of the formulas are valid for computing the reverberation time.

A7. REVERBERATION TIME FORMULAS

The general formula for reverberation time, commonly termed the Norris-Eyring formula is:

$$T = \frac{0.049V}{-S \log_e (1 - \bar{\alpha})}$$

$$= \frac{0.049V}{-S [2.3 \log_{10} (1 - \bar{\alpha})]}$$

where V = room volume, cubic feet

S = total room surface, square feet

$\bar{\alpha}$ = average absorption coefficient $= a/S$

a = total room absorption, sabins

If the average absorption coefficient $\bar{\alpha}$ of the room surfaces is fairly small, the denominator of the formula, $-S \log_e (1 - \bar{\alpha})$, is approximately equal to $\bar{\alpha}$, and the general formula, rounding off the factor 0.049, may be reduced to the approximate or Sabine formula

$$T = \frac{0.05V}{a}$$

For values of average coefficient $\bar{\alpha}$ of less than 0.20, which covers most auditoriums, the two formulas agree within 10 percent, which is close enough to justify the use of the simpler formula in practical work. Higher values of $\bar{\alpha}$ may occur in calculations of broadcast or recording studios, or other special purpose rooms, in which cases the Norris-Eyring formula should be used.

A8. SOUND PRESSURE LEVEL — DECIBEL SCALE

Sound pressure level (SPL) is defined as sound pressure when measured on the decibel (db) scale. The decibel scale is a logarithmic or percentage scale which is laid out in such a way that each successive decibel step in sound pressure level is equal to an increase of approximately 12 percent in sound pressure. A more important relation is that of sound pressure level to sound energy, which is proportional to the square of the sound pressure. In this case, a one-decibel increase in sound pressure level is equal to approximately a 26 percent increase in *sound energy*. (See Definition A4.) Ten successive steps of one decibel are therefore equal to 10 successive increases in energy of 26 percent, which comes out to be exactly a 10-times increase in sound energy. Similarly, a 20-db increase in SPL is equal to a 100-times increase in energy; a 30-db increase corresponds to a 1000-times energy increase, etc. In the other direction, a 1-db decrease in SPL equals an energy decrease of approximately 21 percent, and a 10-db decrease is

³Adapted from C. M. Harris, *Journal of the Acoustical Society of America*, Vol. 35, p. 14, 1963.

equal to a decrease in energy to $\frac{1}{10}$ th of the initial value, or 90 percent.

According to this scale, the difference in SPL corresponding to two sound energies E_1 and E_2 is given by the equation

$$\begin{aligned} \text{SPL}_1 - \text{SPL}_2 &= 10 \log_{10} (E_1/E_2) \quad \text{decibels} \\ &= 10 \log_{10} (P_1^2/P_2^2) \\ &= 20 \log_{10} (P_1/P_2) \end{aligned}$$

where P_1 and P_2 are the sound pressures corresponding to the respective energies.

The decibel scale is therefore a relative scale expressing only fractional or percentage changes in sound pressure or energy. By establishing a standard reference pressure, however, the decibel scale may be used to measure sound pressures or energies on an absolute basis. This reference pressure has been arbitrarily standardized with a value of 0.0002 dynes per sq. cm. and is set equal to zero decibels. A sound pressure level given in decibels, therefore, denotes a definite absolute value of sound pressure or energy as long as the reference pressure is stated or implied. A sound pressure level of zero db is just below that of the faintest sound audible to the average ear, and a SPL of 120 db, equal to 1,000,000 times as much pressure, or 1 trillion times as much energy, is a sound so loud as to cause at least temporary deafening and a feeling sensation in the ear as well as hearing. Representative values of the SPL in decibels of common sounds are shown in Fig. A-3.

A9. SOUND PRESSURE LEVEL OF DIRECT, REFLECTED, AND TOTAL SOUND

The SPL of the directly transmitted sound at a distance of D feet from a non-directional source of W watts sound power output is given by

$$\text{SPL}_D = 10 \log_{10} W - 20 \log_{10} D + 119.6 \text{ db}$$

The SPL of the reflected sound in a room having an absorption of a sabins due to a non-directional source of W watts is

$$\text{SPL}_R = 10 \log_{10} W - 10 \log_{10} a + 136.4 \text{ db}$$

	Deci- bels	Threshold of Feeling
Deafening	120	Thunder, Artillery Nearby Riveter Elevated Train Boiler Factory
	110	
	100	
Very Loud	90	Loud Street Noise Noisy Factory Truck Unmuffled Police Whistle
	80	
	70	
Loud	60	Noisy Office Average Street Noise Average Radio Average Factory
	50	
	40	
Moderate	30	Noisy Home Average Office Average Conversation Quiet Radio
	20	
	10	
Faint	0	Quiet Home or Private Office Average Auditorium Quiet Conversation
Very Faint		Rustle of Leaves Whisper Sound Proof Room Threshold of Audibility

Figure A-3. Sound Pressure Levels of Common Sounds and Noises.

The difference in SPL between reflected and direct sound due to a given source at a distance D is

$$\text{SPL}_R - \text{SPL}_D = 20 \log_{10} D - 10 \log_{10} a + 16.8 \text{ db}$$

The SPL of the combined direct and reflected sound is

$$\begin{aligned} \text{SPL}_T &= 10 \log_{10} [\log_{10}^{-1}(\text{SPL}_D/10) \\ &\quad + \log_{10}^{-1}(\text{SPL}_R/10)] \end{aligned}$$

The direct, reflected, and total sound pressure levels shown in Fig. 13 are produced by a non-directional source having approximately 0.01 watt power output.

APPENDIX B

SOUND ABSORPTION COEFFICIENTS OF GENERAL BUILDING MATERIALS AND FURNISHINGS

Complete tables of coefficients of the various materials that normally constitute the interior finish of rooms may be found in the various books on architectural acoustics. The following short list will be useful in making simple calculations of the reverberation in rooms.

Materials	Coefficients					
	125 cps	250 cps	500 cps	1000 cps	2000 cps	4000 cps
Brick, unglazed	.03	.03	.03	.04	.05	.07
Brick, unglazed, painted	.01	.01	.02	.02	.02	.03
Carpet, heavy, on concrete	.02	.06	.14	.37	.60	.65
Same, on 40 oz. hairfelt or foam rubber	.08	.24	.57	.69	.71	.73
Same, with impermeable latex backing on 40 oz. hairfelt or foam rubber	.08	.27	.39	.34	.48	.63
Concrete block, coarse	.36	.44	.31	.29	.39	.25
Concrete block, painted	.10	.05	.06	.07	.09	.08
Fabrics						
Light velour, 10 oz. per sq. yd., hung straight, in contact with wall	.03	.04	.11	.17	.24	.35
Medium velour, 10 oz. per sq. yd., draped to half area	.07	.31	.49	.75	.70	.60
Heavy velour, 18 oz. per sq. yd., draped to half area	.14	.35	.55	.72	.70	.65
Floors						
Concrete or terrazzo	.01	.01	.015	.02	.02	.02
Linoleum, asphalt, rubber or cork tile on concrete	.02	.03	.03	.03	.03	.02
Wood	.15	.11	.10	.07	.06	.07
Wood parquet in asphalt on concrete	.04	.04	.07	.06	.06	.07
Glass						
Large panes of heavy plate glass	.18	.06	.04	.03	.02	.02
Ordinary window glass	.35	.25	.18	.12	.07	.04
Gypsum board, 1/2" nailed to 2 x 4's 16" o.c.	.29	.10	.05	.04	.07	.09
Marble or glazed tile	.01	.01	.01	.01	.02	.02
Openings						
Stage, depending on furnishings			.25 —	.75		
Deep balcony, upholstered seats			.50 —	1.00		
Grills, ventilating			.15 —	.50		
Plaster, gypsum or lime, smooth finish on tile or brick	.013	.015	.02	.03	.04	.05
Plaster, gypsum or lime, rough finish on lath	.02	.03	.04	.05	.04	.03
Same, with smooth finish	.02	.02	.03	.04	.04	.03
Plywood paneling, 3/8" thick	.28	.22	.17	.09	.10	.11
Water surface, as in a swimming pool	.008	.008	.013	.015	.020	.025
Air, sabins per 1000 cubic feet					2.3	7.2

ABSORPTION OF SEATS AND AUDIENCE

Values given are in sabins per person or unit of seating

	125 cps	250 cps	500 cps	1000 cps	2000 cps	4000 cps
Audience, seated, depending on spacing and upholstery of seats	2.5-4.0	3.5-5.0	4.0-5.5	4.5-6.5	5.0-7.0	4.5-7.0
Seats, heavily upholstered with fabric	1.5-3.5	3.5-4.5	4.0-5.0	4.0-5.5	3.5-5.5	3.5-4.5
Seats, heavily upholstered with leather, plastic, etc.	2.5-3.5	3.0-4.5	3.0-4.0	2.0-4.0	1.5-3.5	1.0-3.0
Seats, lightly upholstered with leather, plastic, etc.			1.5-2.0			
Seats, wood veneer, no upholstery	.15	.20	.25	.30	.50	.50
Wood pews, no cushions, per 18" length			.40			
Wood pews, cushioned, per 18" length			1.8-2.3			

APPENDIX C.

Classification of Products by Appearance and Composition Employed in the Acoustical Materials Association's *Performance Data on Architectural Acoustical Materials*, Bulletin XXIV — 1964.

TABLE No. DESCRIPTION

- 1 Regularly Perforated Cellulose Fiber Tile
- 2 Random Perforated Cellulose Fiber Tile
- 3 Textured, Finely Perforated, Fissured or Simulated Fissured Cellulose Tile
- 4 Cellulose Fiber Lay-In Panels
- 5 Perforated Mineral Fiber Tile
- 6 Fissured Mineral Fiber Tile

TABLE No.

DESCRIPTION

- 7 Textured, Finely Perforated or Smooth Mineral Fiber Tile
- 8 Membrane-Faced Mineral Fiber Tile
- 9 Mineral Fiber Lay-In Panels
- 10 Perforated Metal Pans with Mineral Fiber Pads
- 11 Perforated Metal Lay-In Panels with Mineral Fiber Pads
- 12 Mineral Fiber Tile Rated as Part of Fire Resistive Assemblies
- 13 Mineral Fiber Lay-In Panels Rated as Part of Fire Resistive Assemblies
- 14 Perforated Asbestos Board Panels with Mineral Fiber Pads
- 15 Sound Absorbent Duct Lining
- 16 Special Acoustical Panels and Systems

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